Annual Report

MAST Project- Grand Challenge

Aerospace Systems Design Laboratory (ASDL)

Georgia Institute of Technology, Atlanta, GA
December 2010 – December 2011

1. Progress during this Period

1.1. Introduction and Overall Plan

Several major planned milestones were reached during the July 2011 – November 2011 quarter. Upon completion of the second of three years of MAST research, the ASDL team has completed primary construction of all major research tools and obtained preliminary results from each. The primary focus of work was on development of the following components: (1) a Web based Interactive Reconfigurable Matrix of Alternatives (W-IRMA); (2) an Agent Based Modeling Environment for Rapid Scenario Evaluation; (3) USARSim for Higher Capability Agent Based Scenario Simulation; (4) an Experimental Physical Quad rotor for Validation of the Modeling and Simulation Environment; and (5) an Integrated Physics-based Sizing & Synthesis Environment for Micro Aerial Vehicles.

These components are all interrelated, critical information moves between them and ultimately leads to gap analysis. The complete roadmap set forth at the beginning of the year is shown below in Figure 1:

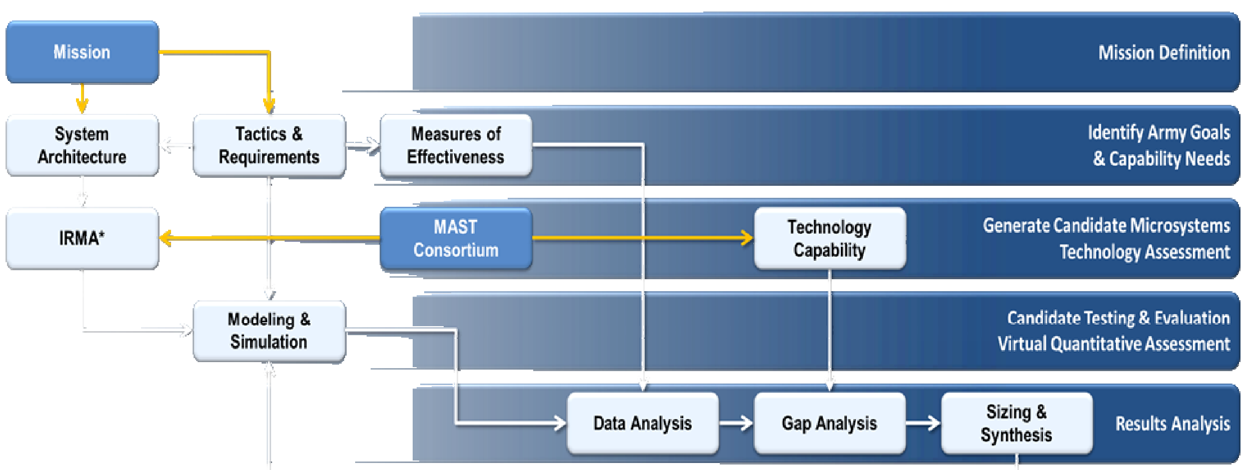

Figure 1: Plan Overview * Interactive Reconfigurable Matrix of Alternatives

defined rigorously and quantitatively. The mission is broken up into operational blocks comprised of required functions gleaned from the Army tactics manual, which constitutes the System Architecture. This functional breakdown, along with information on current state-of-the-art within the MAST consortium, is fed into the Interactive Matrix of Alternatives (IRMA). With this information in hand, IRMA evaluates the entire design space (> 250 billion possible combinations) and finds the highest performing technologies according to the selected mission functions and subsystem choices. As

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
30-01-2012	Annual Research Report	20101201 - 20111230

4. TITLE AND SUBTITLE

Micro Autonomous Systems and Technology
A Methodology for Quantitative Technology Assessment and Prototyping of Unmanned Vehicles

5a. CONTRACT NUMBER

LaRC/ARL Coop NNL09AA0A

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

2A31

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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RDRL-VTV
6340 Rodman Rd
Aberdeen Proving Ground, MD 21005

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

This material is based on work supported by the National Aeronautics and Space Administration, Langley Research Center under the Research Cooperative Agreement No. NNL09AA00A awarded to the National Institute of Aerospace. Any opinions, findings,

14. ABSTRACT

The primary objective of Quantitative Technology Assessment (QTA) is to explore the design space of technology alternatives currently under research by the MAST Consortium, and then quantitatively assess technology impacts on overall mission effectiveness. This seeks to answer two primary research questions: what combinations of Microsystems will best enable mission success, and how to quantify the technology gap between the Warfighter and the technologist. Considering the current work of the MAST consortium, the research of this past year has been heavily focused on rotary and flapping wing platforms. However, recent progress was made to include more general platforms and technologies. This past year, the Interactive Reconfigurable Matrix of Alternatives (IRMA) tool was modified and updated to reflect the three MAST CTA mission scenarios: (1) convoy assistance, (2) non-lethal area protection, and (3) interior building reconnaissance. Results were ranked and then utilized in the modeling and simulation environments. Further, a collaborative, web-based version was developed for online access by all consortium members.

15. SUBJECT TERMS

Micro autonomous systems, matrix of alternatives, unmanned system, conceptual design, sizing, architecture, agent-based modeling, experimentation, scenario simulation, technology tradeoffs

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UU	48	Eric Spero
					19b. TELEPHONE NUMBER *(Include area code)*
					(410) 278-8743

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described in previous reports, IRMA utilizes qualitative and quantitative measures such as Subject Matter Expert (SME) rankings and available physical data to calculate an aggregate score for a single vehicle. IRMA passes the family of concepts to the Agent-Based Modeling Environment for rapid scenario evaluation at a higher level of capability than the qualitative & quantitative measures used within IRMA. The top performing technologies from the Agent-Based Environment are passed into the higher-capability USARSim environment for analysis at even higher fidelity. The final output is a family of concepts that performs the mission most effectively out of an initially unwieldy design problem. This family of concepts is analyzed by using the Sizing & Synthesis (S&S) environment, which attempts to take performance characteristics exhibited by the final family of concepts and through an iterative process, converge on a physical system with the same capability based on currently existing technology. If this process does not yield a converged design, then a 'gap' in performance exists. Identifying and quantifying these gaps is the end goal of ASDL MAST research, and once successful will yield a powerful, integrated system of tools for designing, simulating, analyzing, and predicting the behavior of experimental micro aerial vehicles.

Progressing from work completed during last quarter, IRMA, which enables determination of mission effectiveness of various homogenous technologies for a given mission scenario, was utilized for developing a web-based IRMA It will provide MAST consortium members the capability to access all information and relationships stored within IRMA through a typical web browser. Using this tool, MAST members anywhere can concurrently explore individual possible homogeneous platforms comprised of technologies within the IRMA database, and see a configuration score for their choice.

Further developments were made in both the rapid agent-based modeling and simulation and higher-capability USARSim environments to enable quantitative evaluation of heterogeneous swarms and emergent behavior on mission effectiveness. In the rapid agent-based modeling and simulation environment, individual actors have the capability to work cooperatively by sharing virtual environment information, and differing performance characteristics in order to simulate a heterogeneous swarm. Beginning in Q4, the higher-capability USARSim environment has been refitted for both ROS integration and performing Verification & Validation (V&V) with the physical quad-rotor. Both modifications have increased the environment fidelity by using more intelligent autonomy algorithms and simulating an existing physical area.

The experimental quad-rotor has completed its physical construction and performed simple obstacle avoidance behavior. Similar to the USARSim environment, the quad-rotor is undergoing software modifications to incorporate processing schemes used in the virtual environment on-board and in a physical environment. Full experimental runs for V&V of the higher-capability USARSim environment are soon to follow.

The integrated S&S environment is operational and currently undergoing testing. Once validated, this tool will close the loop by working iteratively to size the vehicle. The process is based on operational and energy requirements indicated by the modeling and simulation environment and current technology capability, which is fed into the Modeling and Simulation (M&S) environment for reevaluation. This process will ultimately lead to a sized vehicle(s) meeting all performance and mission-based constraints.

However, if convergence is not reached, this implies the current state of technology is not sufficient to perform the mission according to the requirements defined. In the subsystems that prevent convergence, a gap in technology exists. Therefore, the quantitative data obtained will result in gap analysis, which answers the following two questions for each mission scenario: What is the state of the art in the pertinent technologies? What level of technology capability is needed to build a MAST system? All of these components fit together like the pieces in the jigsaw puzzle, as in Figure 2 shown below.

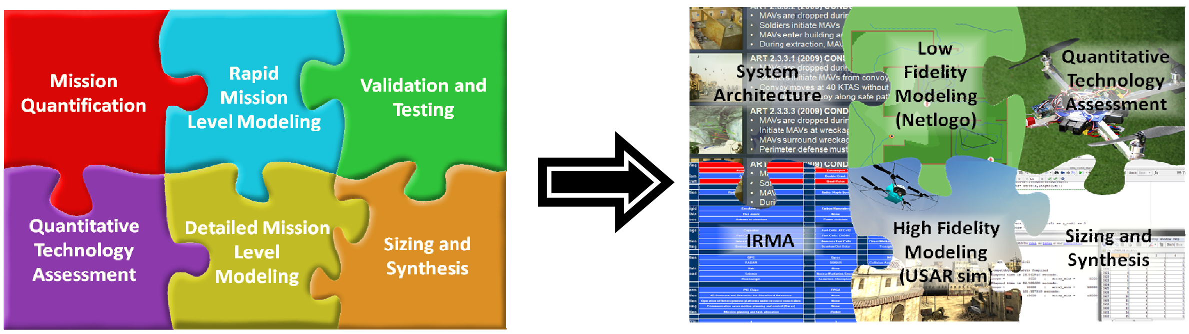

Figure 2: Major Research Tools

Further details of progress made on each research issue during this period are described in subsections below.

1.2. Research Questions and Accomplishments

The major accomplishments and capabilities achieved are summarized in the table below. The research issues set forth in this year's plan are correlated to the components developed and how those are answered based on the capabilities achieved. Further details of each of the components are in following sections.

Table 1: Major Accomplishments and Capabilities Achieved

Major Accomplishments	Significance to MAST	Capabilities and Knowledge Achieved
Interactive Reconfigurable Matrix of Alternatives (IRMA)	• "How can various MAST technologies be evaluated rapidly for mission specific scenarios?" • "How to bind the enormous combinatorial space of integrated systems, technologies, and scenarios?" • "How can technology gap be quantified?"	Capability to rapidly evaluate billions of different MAST technology combinations for homogenous solutions, resulting in design space sweep.
Web Based Interactive Reconfigurable Matrix of Alternatives (W-IRMA)	• "How can all members of MAST consortium utilize IRMA for evaluation technologies in mission specific scenarios and determining compatibilities between them?"	Provides a web based platform for utilizing IRMA.
Low-Fidelity Agent-Based Modeling & Simulation Environment	• "How can integration effects of various platforms be modeled, and how are the resulting emergent behaviors identified within the microsystem ensemble?" • "How can technology gap be quantified while considering swarm behavior?"	Capability to rapidly evaluate various MAST technologies and platforms for specific mission scenario. It also enables modeling and simulation of ensemble behavior for heterogeneous systems, emergent behavior and resulting synergy.
Higher-Capability Agent-Based Modeling & Simulation Environment	• "How can specific mission scenarios be simulated from start to end in great detail in a virtual world that is reasonably accurate?" • "How to verify and validate the system-of-systems environment?" • "How can technology gap be quantified while considering all aspects of a mission scenario?"	Capability to model and simulate mission scenarios in 3D detailed visualization with agent based logic and physics based world.
Experimental Quad-rotor	• "How can modeling and simulation environments be validated to ensure that the accuracy is reasonable?"	An experimental quad-rotor provides a test bed for testing of various algorithms and validation of modeling and simulation environment.
Sizing and Synthesis Tool	• "What is the best approach to synthesizing and sizing a microsystem?" • "How can technical feasibility of the vehicles in modeling and simulation environment be evaluated based on current state of the art technologies?"	Physics and energy based constraint methodology for sizing MAST vehicles. It provides an iterative approach to actual sizing of vehicles that are able to successfully complete given mission.

1.3. Quantitative Technology Assessment

The primary objective of Quantitative Technology Assessment (QTA) is to explore the design space of technology alternatives currently under research by the MAST Consortium, and then quantitatively assess technology impacts on overall mission effectiveness. This seeks to answer two primary research questions: what combinations of Microsystems will best enable mission success, and how to quantify the technology gap between the Warfighter and the technologist. Considering the current work of the MAST consortium, the research of this past year has been heavily focused on rotary and flapping wing platforms. However, recent progress was made to include more general platforms and technologies.

As a first step in technology assessment, a specialized tool IRMA was developed previously to enumerate alternatives within a large combinatorial design space. It is based on a functional decomposition of the technologies/subsystems (e.g. radar), their technological attributes (e.g. range), and MAST low level functions (e.g. detect target). Combined with response surface metrics from higher level simulations, the expected end results is to down-select specific technologies that are best suited for specific missions and then model these technologies in the agent based environment.

This past year, the IRMA was modified and updated to reflect the three MAST mission scenarios: (1) convoy assistance, (2) non-lethal area protection, and (3) interior building reconnaissance. Results were ranked and then utilized in the modeling and simulation environments. Further, a collaborative, web-based version was developed for online access by all consortium members. This will enable every member to access the developed technology database, view current technologies, update specifications for their technologies, and explore various combinations resulting in homogenous solutions. Details are given in the following subsection.

1.3.1. Development of Web-based IRMA and Modifications to IRMA

IRMA, the Interactive Reconfigurable Matrix of Alternatives, is a dynamic database which allows a user to select between various platform and subsystem types, then define a mission scenario by functionally weighting low-level activities like ‘Move to GPS waypoint’, in order to filter, select, and rank a large selection of design alternatives for their chosen mission. In order to accomplish this, each mission scenario is compiled of a list of operation functions of which it entails. These operation functions are the ”What”s of the Matrix of Alternatives (MoA) and make up the capabilities, requirements, and needs of the mission. Platform configuration constitutes the “How”s of IRMA analysis, as each subsystem choice (e.g. Sensors: LIDAR, Camera, SONAR) is qualitatively or quantitatively ranked against the other options in such categories as weight and power consumption. Incompatible selections are automatically removed from consideration by an easily updated incompatibility matrix, significantly reducing computation time. The IRMA database then takes the user’s selections and ranks the “What”s against “How”s, and outputs to the user a reduced family of vehicles from an initially cumbersome (> 250 billion possible platform selections) design space which has been custom-tailored to their mission scenario.

IRMA is a complex database based on the Analysis of Alternatives (AoA) military process, which aims to refine alternative's options and criteria, gain consensus, reduce uncertainty, and ultimately assist in choosing the optimal alternative.

The IRMA technical database is continuously updated to include the latest technology alternatives from the MAST Consortium. Every technology, including those currently available and technologies currently in research and development, has quantitative information such as Technical Readiness Level (TRL), mass, velocity, etc. By outlining over a hundred operation functions derived from mission plans, an IRMA user can quantitatively assess mission effectiveness and determine a robust combination of technologies. Since IRMA is dynamic and sortable, the user can easily specify platforms of interest (such as rotary and/or flapping wing). IRMA is an incredibly useful tool that provides researchers with access to knowledge of technology combination capabilities, which is why everyone in the MAST Consortium should be able to access IRMA's features.

The web-based IRMA (W-IRMA) is a database-driven preliminary design application that is a dynamic, reconfigurable, user-friendly, and accessible MoA. W-IRMA has all the benefits of IRMA while storing and managing information through a common database that users can concurrently access on a typical web browser. An Apache web server handles all server-based communication. Figure 3 shows a visual representation of the W-IRMA structure.

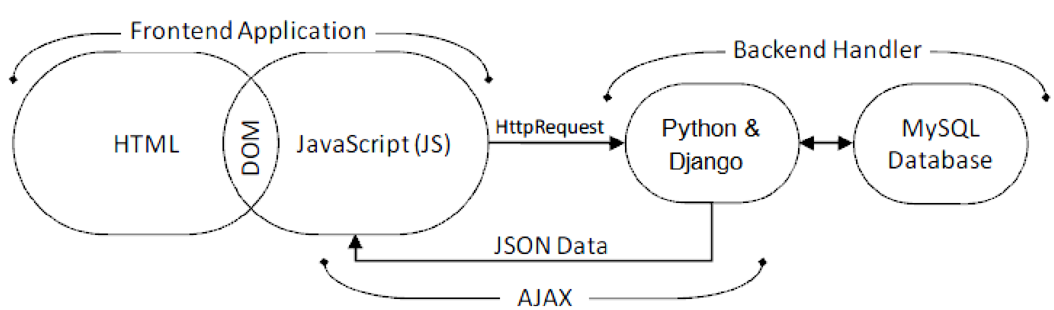

Figure 3: Schematic of MAST W-IRMA Structure

The frontend application of W-IRMA uses a combination of HTML, DOM, and JavaScript. AJAX and JSON data handle HttpRequests. The configuration allows the user to manually weight mission task functions or choose from a standard weighting to reflect the requested mission scenario. For example, the task "Generate Jamming Signal" may be required, and thus weighted heavily, for a non-lethal protection scenario, but not needed for a general reconnaissance mission. Next, the user specifies vehicle attributes desired and W-IRMA determines the 'score' of the vehicle. Conversely, the user is able to run a full-factorial analysis of the design space, or select certain attributes and run a reduced analysis, and generate rankings for all possible vehicles, although this process is more time consuming and more suited to execution in its stand-alone version.

Django and Python perform backend calculations by accessing IRMA matrices uploaded into a MySQL database, which consists of three main sections. The first web-based database matrix contains quantitative vehicle attribute data for each MAST alternative, such as required power, TRL, or cost. The second database matrix compares every MAST alternative against each other to account for any incompatibilities. For example, the vehicle cannot have a fixed wing and a flapping wing, so a "1" represents the relationship between these two attributes and W-IRMA does not let the user pick both. Lastly, each mission task holds quantitative vehicle attribute data (e.g. identifying targets implies a dependency on processing power, but not vehicle mass). When a user designs a vehicle using W-IRMA they choose an alternative for each subgroup (e.g. Locomotion, Power, or Communication). For a given alternative, a summed value of vehicle attribute ranks multiplied by the mission task ranks and the mission task weights constitutes a configuration score. W-IRMA then calculates. W-IRMA calculates the total vehicle score by summing this value for all chosen alternatives.

Our team is looking into measuring the effectiveness of this tool and continuously exploring ways to keep the tool user-friendly while incorporating new technologies as they become available.

1.4. Mission Level Modeling: MAST Modeling and Simulation

In order to evaluate any specified mission scenario in detail, mission level modeling and simulation environment is necessary. Two such environments were developed and test: Low-fidelity and high capability. The use of low fidelity, first-level simulation enables rapid assessment of available and hypothetical technology alternatives, which makes it very useful for the task of quantitatively evaluating the reduced but still large family of concepts resulting from IRMA analysis. The more advanced simulations performed by USARSim simply demand too many resources to investigate this design space, however by removing the less viable alternatives, higher capability simulations can be used to examine the most vehicles in far greater depth.

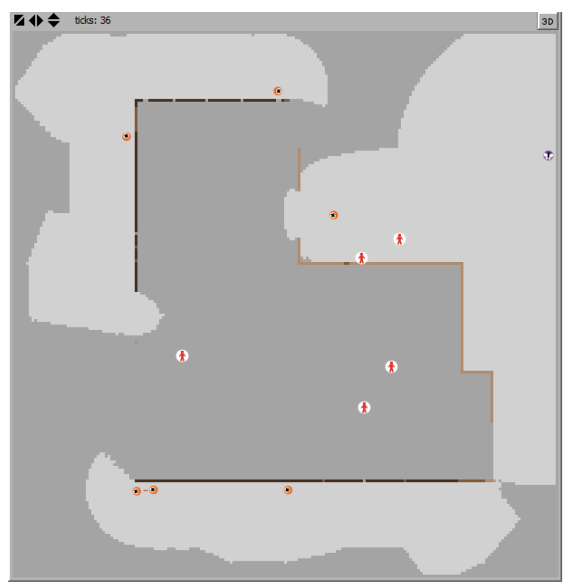

Figure 4 – Agent Based Modeling Space

The lower fidelity model utilizes an agent-based framework, allowing simulation to investigate emergent behaviors of cooperative MAST systems. The software in use Netlogo enables the user to modify desired scenarios and alter the programming of MAST agents providing the means to rapidly test algorithms and examine whether the resultant behavior matches the desired outcome. Different types of MAST platforms are selectable for deployment within the simulation, and each platform is customizable. The characteristics of these platforms—such as speed, turn rate, sensor range, etc—can be quantitatively adjusted prior to each simulation run. By varying these values over multiple runs, the simulation results are able to draw trends between system properties and mission performance.

Outcomes from the simulations are currently being investigated and iterated upon to improve fidelity and efficiency. So far the most developed mission scenarios are the interior building reconnaissance and the non-lethal protection missions. The interior reconnaissance has been completed and its results are being obtained. Similar mapping and navigation methods are being applied to the non-lethal protection scenario, with some changes to MAST system behavior to allow interaction with and reaction to enemy units. Development of the convoy assistance scenario will shortly follow the completion of the other two scenarios.

The lower-fidelity modeling and simulation environment was designed to provide a first level quantitative assessment of technology competitions for rapid evaluation of the parametric space. The model provides an initial filter to the higher levels of modeling and simulation, in this case USARSim, resulting in higher-capability simulation time focused on a better defined set of alternatives. Additionally, the lower-fidelity environment provides an initial perspective into the behaviors of MAST vehicle swarms in mission environments. Particularly, the model provides a way to quantify emergent behaviors and to understand how these effects influence mission effectiveness parameters. In the end, the lower-fidelity environment is a contributing element to gap analysis. The model creates an environment where both today's state of the art is simulated and a future ideal is investigated to determine existing gaps in performance parameters.

A simulation environment for each mission scenarios under investigation will be developed within Netlogo, an agent based modeling and simulation environment. Ultimately, the MAST vehicles themselves are condensed down to black boxes represented instead by a collection of basic mission performance parameters. These parameters are used to quantify all aspects of the systems, including locomotion, communication, sensory input, and others. The primary differences between missions are scenario objects, how vehicles move and operate, and how vehicles interacted with their environment, including interactions amongst vehicles and enemy units. The outputs of these simulations are the relevant mission effectiveness parameters, used to quantify how the systems performed at the mission level. While the performance parameters are consistent between missions, the effectiveness readings can vary and may include such factors as percentage of the map discovered, time to reach certain mission goals, and microsystems lost during completing the mission. These final parameters are an important metric in performing a final gap analysis. The mission performance parameters are shown in Table 2 – Measures of Performance.

Table 2 – Measures of Performance

Measures of Performance
Speed
Turn Rate
Avoidance Distance
Sensor Viewing Angle
Sensor Detection Distance
Communication Distance
Operating Height
Clearance Height
Vehicle Size

The lower-fidelity environment helps to answer several of the research questions posed in this study. First, the lower-fidelity environment plays a major part in answering what combination of technologies best enable accomplishing a given mission. The environment is designed to allow any combination of technologies to be represented as a condensed combination of technology impacts, or mission performance parameters. Combining this capability with a Design of Experiments (DOE) methodology, it is possible to parametrically explore the concept space for both cases of solo vehicle operation as well as swarms of either homogeneous or heterogeneous sets of systems. Using this approach, cutoffs in performance metrics can easily be determined in order to achieve specific mission level goals. This process also works to answer what vehicle factors can increase mission success probability.

Secondly, the lower fidelity environment plays a role in answering *How to quantify the technology gap* between what is capable with the state of the art today, and what is the ideal for a given mission. This question actually builds off of the first, because it is necessary to determine where technology capability needs to be in order to perform any kind of gap analysis. Using the lower fidelity environment's capability to reduce complex MAST vehicles down to discretized sets of performance parameters, the current state of the art can be evaluated based on its viability in any given mission. It is simply an exercise of taking information on what technologies exist today, and converting this understanding into a set of mission performance parameters. From here, it is a case of examining this set of performance parameters in a mission environment, similar to the parametric studies used to determine the future requirements necessary to complete the mission.

Finally, the lower fidelity environment is critical in determining *how emergent behaviors of the microsystem can be identified and quantified* between various MAST vehicles in a mission, as well as between the vehicles and their environment. Emergent behavior is the concept that more complex behaviors develop out of the interactions amongst elements in an environment. These behaviors will ultimately have an impact on mission level success, and as such require a method of quantifying these impacts. Agent based modeling is designed partially for this reason. Using the lower fidelity environment, it is possible to look at a wide range of combinations of homogeneous and heterogeneous systems and to see their effect on the final mission effectiveness parameters.

Currently, the model for the interior building reconnaissance mission has been completed and is being used to generate results. Although modifications will continue to be made as new and better information become available, the initial results are showing some insightful trends. Below are a few of the most interesting data sets. Currently, out of the parameters which affect the range of the interior space examined, the velocity of the vehicle has the most notable impact on what ranges are possible given a set of mission performance metrics. Figure 5 – Speed vs. Percent of Interior Space Discovered below shows the percentage of the interior space uncovered. Note that there is an effective frontier which helps to define the minimum speed necessary to reliably reach certain coverage ranges.

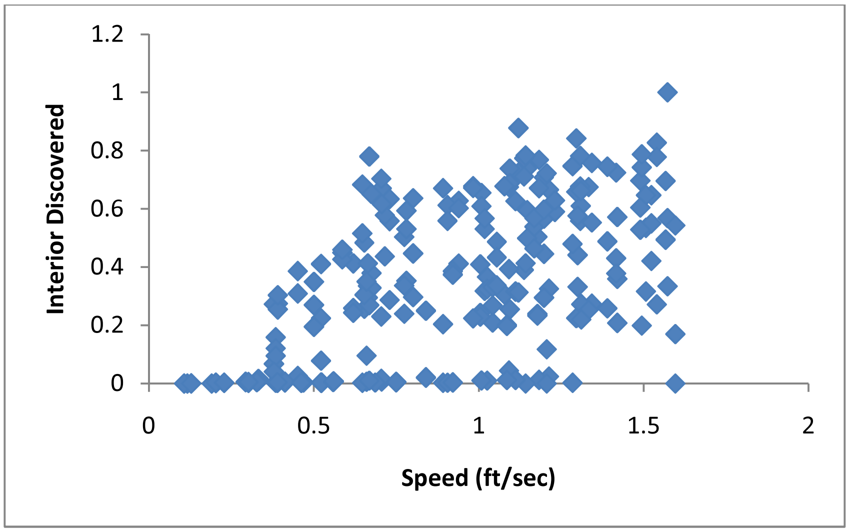

Figure 5 – Speed vs. Percent of Interior Space Discovered

Next in **Error! Reference source not found.** is the effective mission time versus the vehicle speed. Again, a frontier appears to define minimum speeds to achieve certain time goals. All cases were run with two active MAST units operating in a simple building layout for a maximum of five minutes. Within the environment were enemy units that could destroy the MAST vehicles should they be detected.

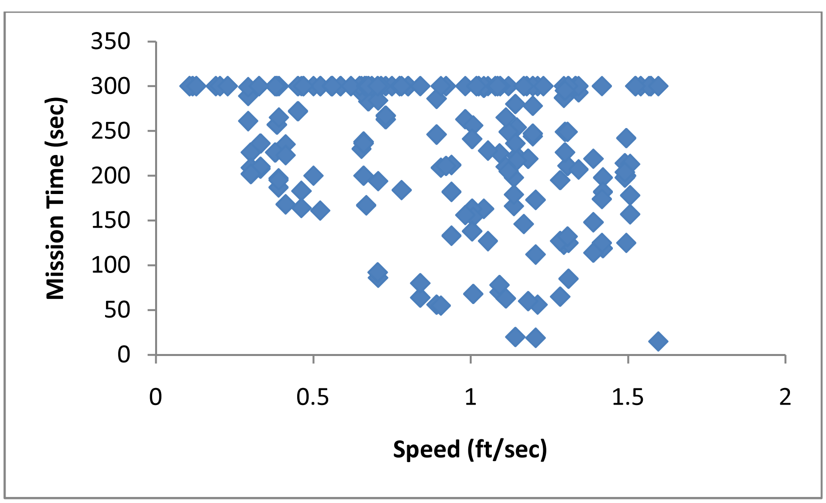

Figure 6 – Speed vs. Time to Reach Mission Completion

Looking at another performance metric, in this case detection distance, a similar analysis is performed. In Figure 7 - Detection Distance vs. Percent of Interior Space Discovered below is a plot of the view distance against the percentage of the interior space discovered. Although a frontier exists similar in nature to that seen with the speed, the change in minimum view distance required to meet specific coverage of the interior space goals is less pronounced. This suggests that this performance metric is less important compared to others and that powerful sensors with wide sight arcs are necessary.

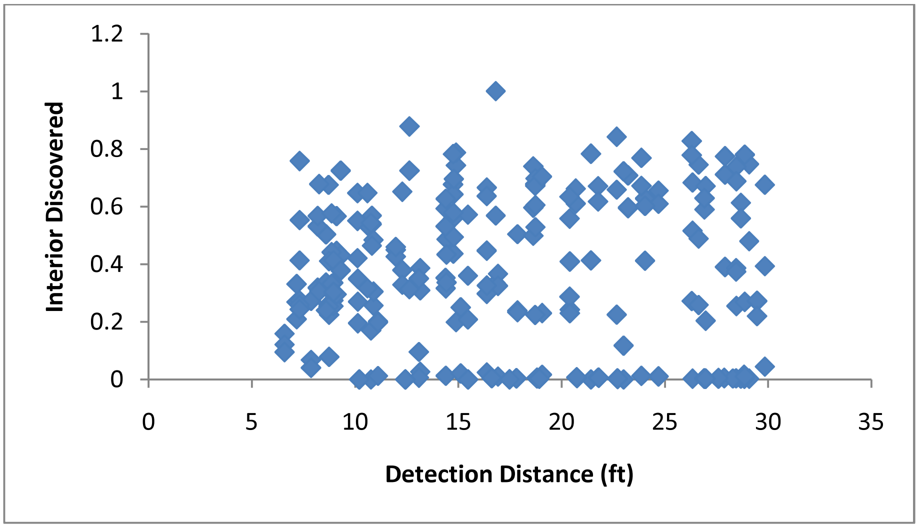

Figure 7 - Detection Distance vs. Percent of Interior Space Discovered

The next immediate goal is to finish building the modeling and simulation environments for the perimeter defense and convoy assistance missions. Parametric DOE studies will continue to be performed to define elements necessary for gap analysis.

1.4.1. USARSim for Higher-Fidelity Agent Based Scenario Simulation

1.4.1.1. Introduction

In order to gather detailed performance characteristics of the highest possible fidelity, the ASDL MAST team has been developing the Unified System for Automation and Robot Simulation (USARSim) for simulating the behavior of fully integrated vehicles within a realistic environment. This tool is responsible for taking the reduced family of concepts indicated for further study by the rapid evaluation agent-based environment and repeating their simulation within a higher-fidelity environment. To validate these findings, the higher-capability modeling environment compares its results with those taken from physical runs with the experimental quad-rotor. Once validated, these simulated results are passed to the S&S tool to perform final performance and gap analysis.

As discussed in the Q3 report, USARSim is a bridge between an external program that defines a vehicle's behavior to the Karma physics engine contained within the Unreal Tournament environment. Figure 8 below shows pictorially how these tools fit together.

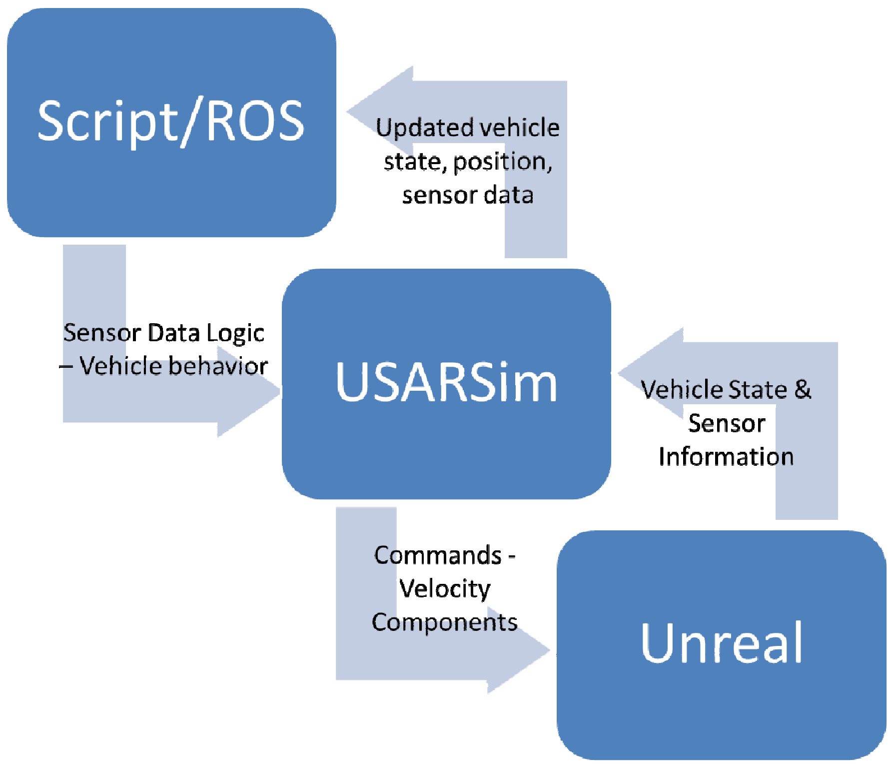

Figure 8: Higher-Capability Modeling Components

Currently the external script contains the logic required for the vehicle to employ wall-following behavior or frontier-based exploration, which allowed the simulation to produce first results on the vehicle's mission performance. The outputs included: total time vehicle was operating, battery level at simulation's end, linear distance covered by the vehicle, and percentage of environment uncovered. Along with tracking the progress of an individual vehicle, the script also supports multiple vehicles simultaneously exploring the same environment, however without inter-communication. The version of USARSim designed for Unreal Tournament 2004 is limited to 16 vehicles, and so in order to facilitate future swarm and complicated behavior simulations, several software upgrades are in progress.

Currently two software upgrades are in progress and nearing completion. The first is the integration of the Robotic Operating System (ROS), which as pictured above replaces the script previously developed for controlling the vehicle's actions within simulation. The ability to link these tools together became publicly available in September, and is still largely under development. ROS integration promises to facilitate comparison studies on software choice and reduced simulation development time, as many technologists developing robotic control algorithms do so within ROS. Upon completion, ROS integration will allow vehicle simulations to use truly intelligent control methods, such as Simultaneous Locating And Mapping (SLAM) and A*. The second software change in progress is upgrading from Unreal 2004 to

Unreal Tournament 3 (UT3). UT3 was released in 2007, and in addition to major aesthetic upgrades on the environments, the level editor released with UT3 is more user-friendly, allowing for quick environment creation. The tools required to link together USARSim and UT3 became available in March 2010, however the tools required for using the Unreal Development Kit (UDK) with USARSim only became available this August. UT3 also boasts an updated physics engine and long-term support, the latter of which cannot be said for Unreal 2004.

In developing this tool, the team has worked towards answering several research questions. First: How can emergent behaviors of the microsystem swarm be identified and quantified? The behavior of a single autonomous platform within a realistic environment is by itself not easy to simulate, and the impact of heterogeneous platforms within an ensemble presents many possibilities for complex behavior. With each new type of platform, more synergistic relationships between platforms become possible, much like the complex relationships found within biological ecosystems. In the biological world, species such as ants individually perform simple sets of behaviors that only when aggregated accomplish complicated feats such as creating and maintaining a colony. The result of the aggregated behavior is called an emergent behavior, requiring mutual cooperation between each individual. Great benefits are expected from emergent behaviors, but there are no current means to assess when and how such patterns may occur. In order to address this question, the USARSim environment has been modified to interface with ROS so intelligent vehicle inter-communication algorithms currently in use and development can be used in simulation. Testing is still ongoing, and results are expected by Q2 of next year.

The second research question to be answered is: How can integration effects of various platforms be modeled in specific mission scenarios and what combination of rotary and flapping wing microsystems would maximize the mission probability of success? For the first portion of this question, each mission scenario must be modeled to a level of fidelity that accurately reflects the mission and its requirements. In the case of Interior Building Reconnaissance (IBR), the simulation environment has been constructed after a physical test location at the MAST center in Joppa, MD as shown in Figure 9 below.

Continuing with constructing the simulation environment after physical locations, several more maps were created using the physical dimensions of areas within the Weber buildings at Georgia Tech. One such map is shown in Figure 10 below simulating the 1st Year Lab at ASDL. Special care was taken in each construction to keep the physical geometry as close to reality as possible, so that results gleaned from simulations taking place within these environments could be of the highest possible fidelity. In particular, since the physical analogue of the Joppa building is currently being used for testing of MAST platforms, the attention given to virtual construction allows for comparison between virtual and physical performance. In this way, virtual performance metrics can point toward particular vehicle configurations that may perform better, and comparable physical experiments taking place can result in more realistic trends to base simulated performance, thus increasing the fidelity of the virtual environment.

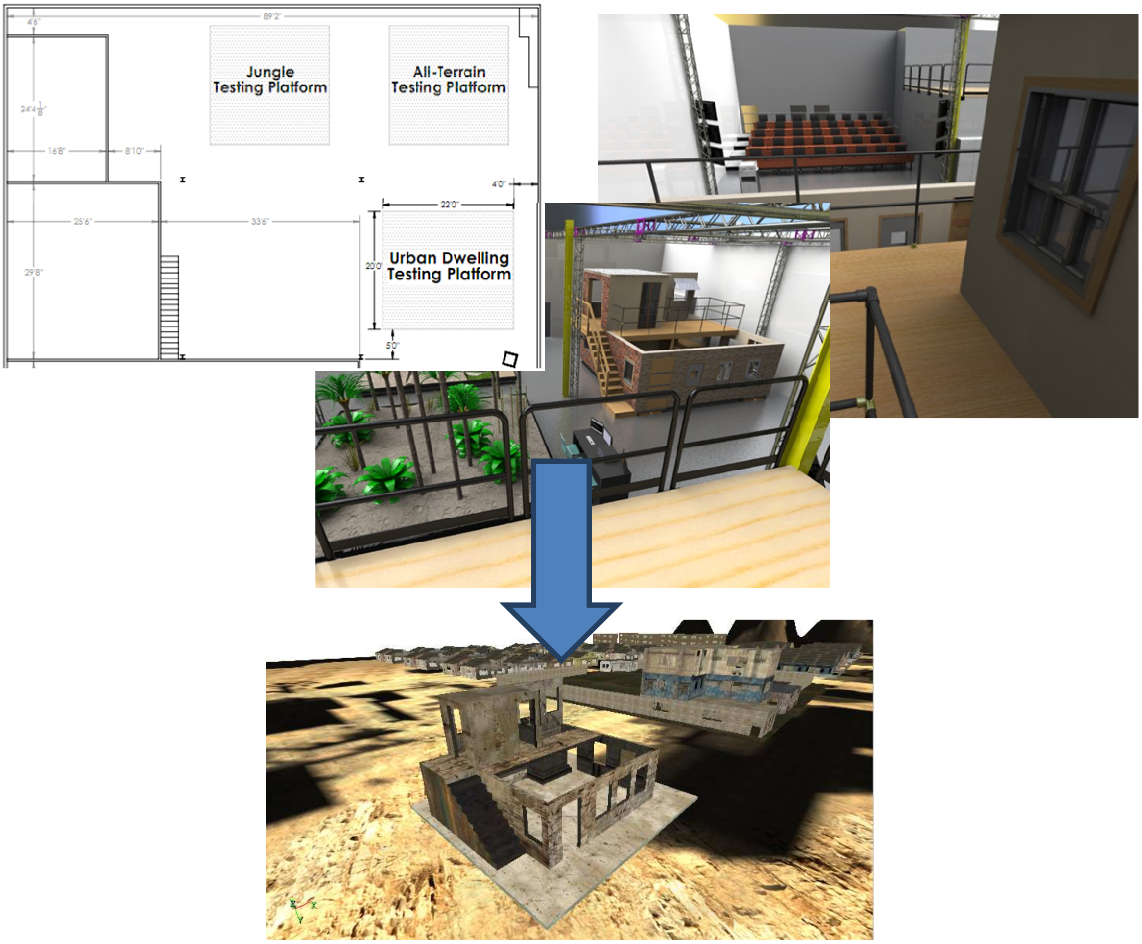

Figure 9: IBR Environment in USARSim

Figure 10: 1st Year Lab with Simulated Quad-Copter

The maps shown in Figure 9 and Figure 10 are useful for simulating IBR, however they are insufficient for simulating the Convoy Assistance (CA) mission. In order to address this issue, a much larger map was constructed for CA inspired by the Black Hawk Down (BHD) scenarios, shown in Figure 11 below. During construction, the area surrounding the Joppa building was expanded to include several city blocks worth of simpler buildings in order to provide adequate size for CA, and a building whose dimensions are taken from a BHD documentary and satellite imagery. Although the other buildings do not have the interior complexity of the Joppa and BHD buildings, exterior obstacles such as fences and staggered placement are included to increase the difficulty of the path-planning task.

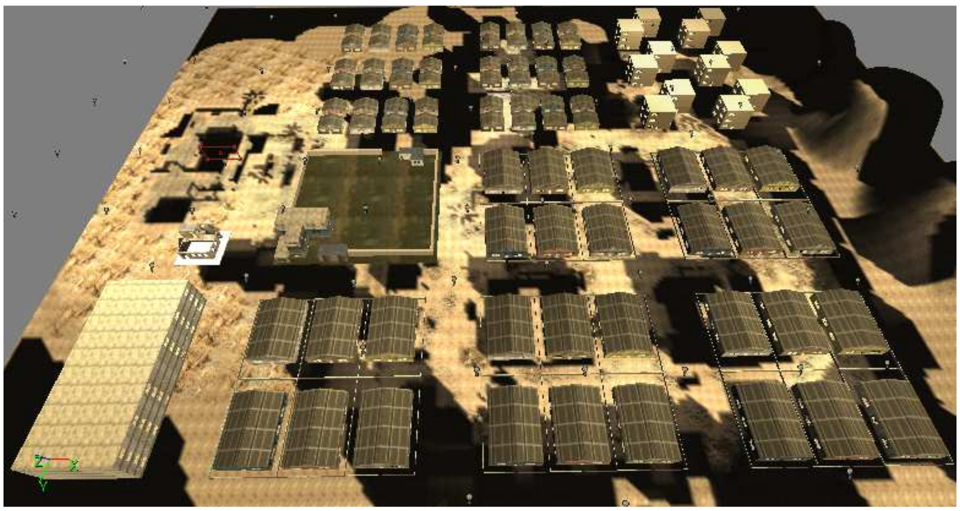

Figure 11: Convoy Assistance Map

In order to answer the second half of this research question, the first research question introduced would have to be answered satisfactorily. Therefore, in order to find the combination of flapping wing and rotary microsystems that maximizes the mission probability of success, the emergent behaviors that exhibit themselves at many different heterogeneous mixture ratios would have to be quantified. As with the previous question, results are expected by Q2 2012.

Finally, the higher capability modeling and simulation environment has sought to answer *how to quantify the operational disconnect and technology gap analysis?* The answer to this question goes hand in hand with the analysis present within the S&S tool that is discussed later. The role of the modeling & simulation environment in regards to this question is that the high-fidelity simulation outputs performance characteristics that the S&S code can operate on to size a vehicle that would be capable of operating at that level. However, if for example the S&S code is unable to find a battery that is able to provide the power level required for the time required, then there is a gap in energy storage capability. The same goes for all systems comprising the vehicle: if the physics-based S&S code is unable to converge on a complete vehicle design based on required performance characteristics, then a gap exists in the current technology level that precludes optimum mission effectiveness. In this manner, the higher-capability USARSim simulation environment along with the S&S tool provide a quantized gap in technology capability to enable top-down and bottom-up strategies for further MAST development.

1.4.1.2. Results

In the current simulation setup, a simulated quad-copter with an Inertial Navigation System (INS) and ranging LIDAR sensor spawns within an environment and immediately begins exploring the environment via a frontier-based algorithm that chooses points within the vehicle's 270 degree field of vision that are the most 'interesting'. Points that meet this criterion are: close to the edge of the vehicle's vision, near an obstruction, or in a recess within an obstruction. The vehicle then moves toward the point it finds most interesting under the influence of two inputs: the wall-following and safety parameters. These parameters scale the reaction of the vehicle's velocity when farther away and closer than a critical safety radius; respectively. Once the vehicle is reaching its destination two more parameters, Position and Rotational Capture, come into play. These two define how close the vehicle has to be in spatial and rotational alignment; respectively, to the point it has chosen to 'capture' it, and then repeat the process. Each time a capture happens however, enemies within the level move further along pre-programmed paths. If the vehicle finds itself in the same area as an enemy when it captures a point, then it suffers damage. If the vehicle suffers three hits of damage, it is destroyed and simulation ends. Otherwise, the simulation will continue in this fashion until either the vehicle destroys itself or its battery is depleted.

Due to the stochastic nature of the simulation, outputs are expected to have significant spread; however trends in the data can still provide insight into the situation being modeled. In order to reduce this spread, only the 1st Year Lab environment shown in Figure 10, and only one start position were used. The first metric considered is the velocity of the vehicle, which is plotted against the total % of the environment explored in Figure 12 below. In the figure, darker shading indicates a higher density of results in that region.

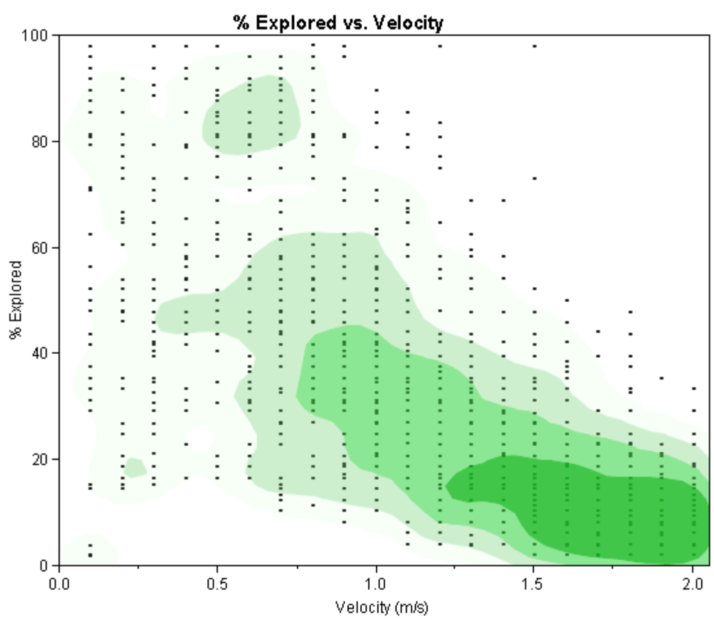

Figure 12: Velocity vs. % Environment Explored

According to the distribution of results seen above, vehicles travelling less than 1 m/s perform better on average. However; qualitatively Figure 12 above shows that vehicles traveling slowly (< 1 m/s) were more capable at carrying out the mission on their own. Vehicles traveling more quickly (> 1 m/s) still perform decently however are not as effective.

The second output metric considered is the total time of simulation, shown in Figure 13 below.

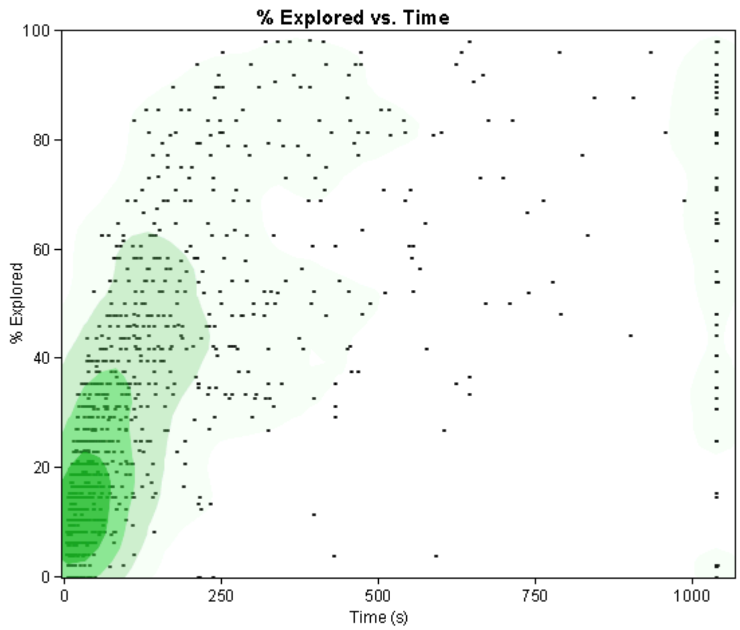

Figure 13: Total Simulation Time vs. % Environment Explored

The distribution of results shows that initially as time increases, more of the environment will be explored, however after ~400s (~7 mins.) there are barely any results until 1036s (~17mins.), the upper limit on simulation time. This trend indicates that on an individual basis vehicles will do their most efficient work within the first 7 minutes of operation, suggesting that individual vehicles should perhaps have a 'cut and run' behavior. This behavior would dictate to the vehicle that after a certain amount of time, even if it has not satisfactorily completed the mission, it should return to its start location. Behaving as such could have an adverse effect on mission effectiveness, but would likely cut down on instances where the vehicle wastes a large amount of time, such as the cases that resulted in the vertical line of results on the right-hand side of Figure 13. Results such as those shown above show ways in which swarm behavior could have a sizable impact on overall mission effectiveness, as individual vehicles are mostly incapable of performing the entire mission themselves, however if linked with several other vehicles sharing their exploration information, the mission could have a much greater chance of success.

Another trend easily seen is shown below in Figure 14 below, which relates percentage of the environment explored with the percentage battery level at end of simulation. Like Total Time above, initial battery use would seem only to help in exploring more of the environment. Also similar to above, there is a point of diminishing return that would also suggest a 'cut and run' behavior. In addition however, the spread of results indicates that in order to have a decent chance at exploring 50% of the environment, the vehicle had to expend ~20% of its battery life. This trend suggests that a vehicle's design has to account for the fact that 1/5 of the battery life must be kept separate from that needed to transport the vehicle to and from the mission site. Therefore, for an IBR mission the vehicle should be deployed nearer to the building rather than further away to ensure mission effectiveness.

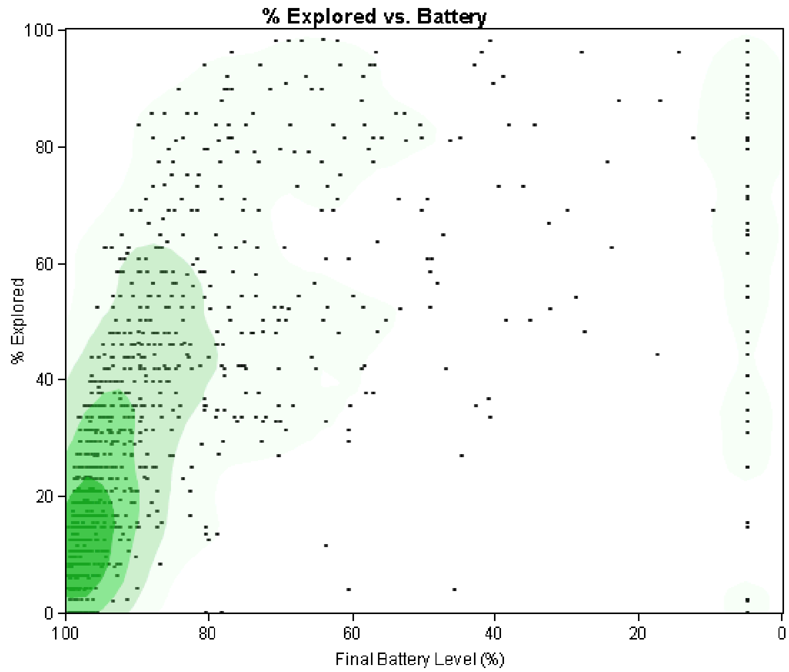

Figure 14: Battery % at End of Simulation vs. % Environment Explored

Another interesting metric is the vehicle velocity's deviation from its input value. During simulation, the vehicle attempts to keep moving at its input value, however reacting to obstructions can cause this speed to be either slower or faster at any given time of simulation. In order to construct this metric, the average velocity is defined

$$\overline{Vel} = \frac{Total\ Distance\ Covered}{Total\ Simulation\ Time}$$

Equation 1: Average Velocity

And the absolute velocity deviation is defined

$$Absolute\ Velocity\ Deviation = \sqrt{\left(\frac{Vel - \overline{Vel}}{Vel}\right)^2}$$

Equation 2: Absolute Velocity Deviation

High values of absolute velocity deviation arise from simulations where the vehicle was frequently traveling at speeds different from the inputted velocity. The effect of the absolute velocity deviation metric on the % environment explored is shown below in Figure 15.

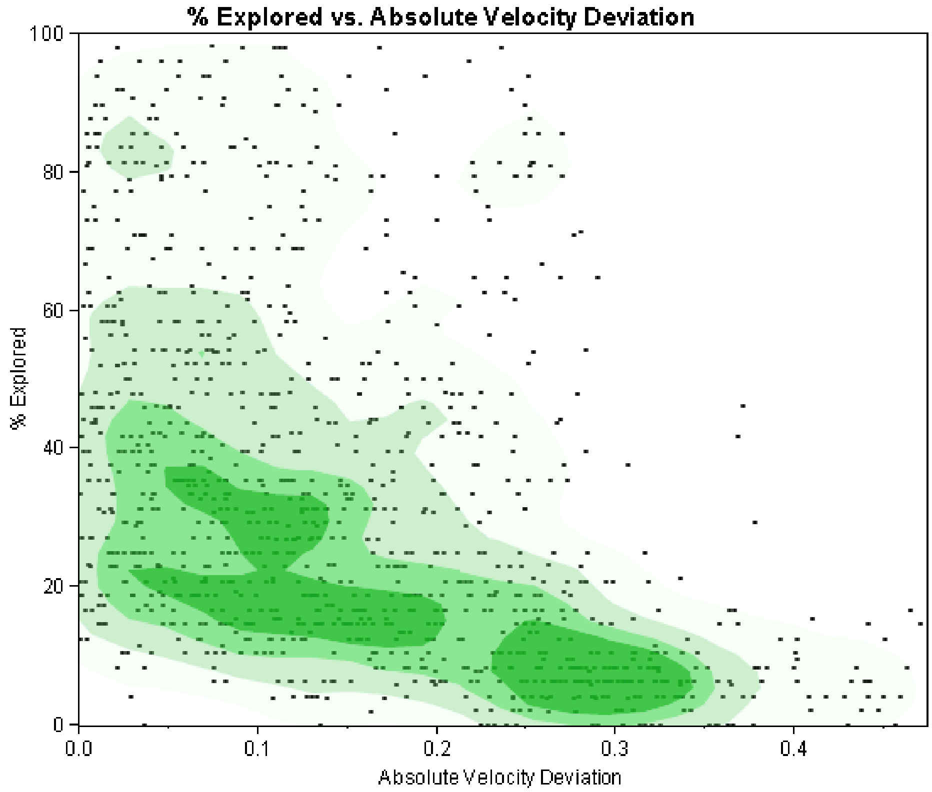

Figure 15: Absolute Velocity Deviation vs. % Environment Explored

As the absolute velocity deviation goes toward zero, there is a definite trend toward higher % exploration. This trend shows that vehicles that did not deviate in their velocity (never slow down or speed up) perform better than those that are more stop-and-go. This suggests that vehicles performing a reconnaissance mission should be equipped to move as fast as they can, all the time. The absolute velocity deviation does not however distinguish between cases where the vehicle was traveling faster or slower than its inputted value. The velocity deviation is defined

$$Velocity\ Deviation = \frac{Vel - \overline{Vel}}{Vel}$$

The effect of velocity deviation on % explored is shown below in Figure 16.

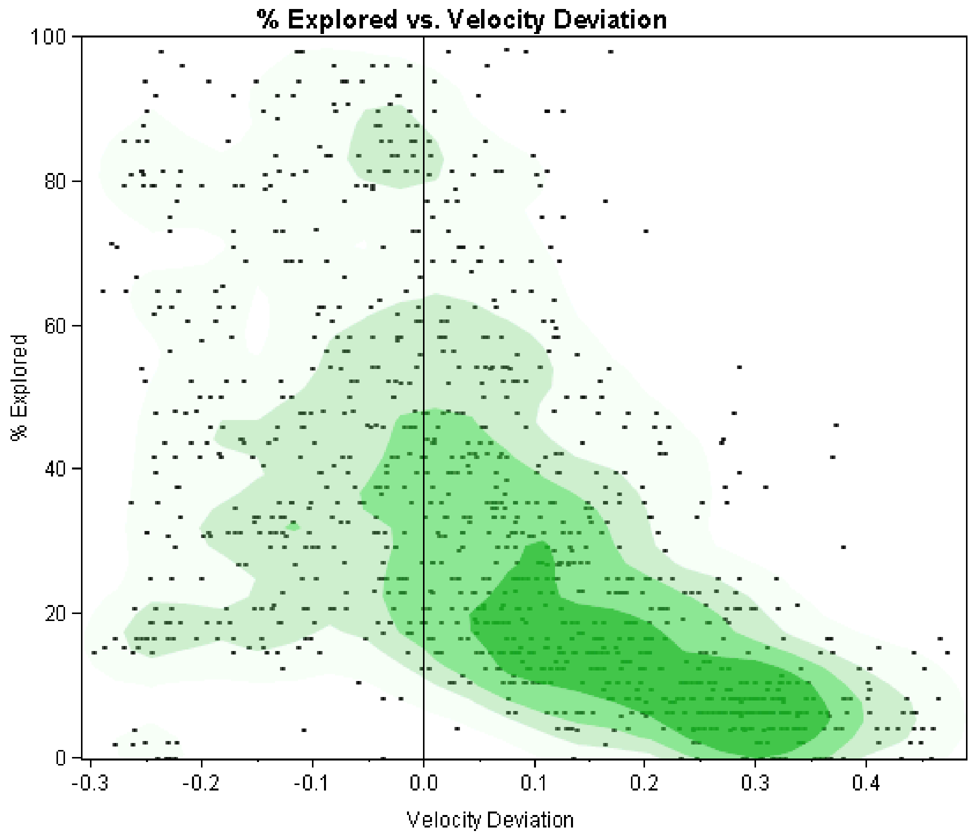

Figure 16: Velocity Deviation vs. % Environment Explored

The above figure shows that ~60% of simulation runs exhibit a positive velocity deviation, meaning that the average velocity is lower than input velocity. There is also a positive trend toward zero from the positive end but not the negative (faster than average); suggesting that going slower than the input velocity hinders mission effectiveness. Since the same trend is not seen on the other side, going faster than the input velocity cannot be described as a method to improve effectiveness. However, it can be said that keeping the velocity deviation as close to 0 as possible will result in higher % explored versus non-zero deviation.

In order to move toward defining an Overall Evaluation Criterion (OEC), 'good' and 'bad' simulation runs are defined to be those in the top 10% of environment explored and those where the vehicle was destroyed or explored < 10% of the environment; respectively. The attributes of both good and bad simulation runs are shown in table below.

Table 3: Good & Bad Attributes

		Position Capture	Rotational Capture	Wall-Following Parameter	Safety Parameter	Velocity	Rotational Velocity
Good	**Mean**	1.22	1.27	4.04	0.11	0.57	0.74
	Standard Deviation	0.50	0.45	1.61	0.06	0.32	0.43
Bad	**Mean**	1.18	1.23	4.02	0.11	1.24	0.81
	Standard Deviation	0.43	0.45	1.72	0.06	0.63	0.44
Difference	**Mean**	0.04	0.04	0.02	0.00	0.67	0.07
	Standard Deviation	0.07	0.00	0.11	0.00	0.31	0.01

The color scale used in the Difference: Mean row of table above runs from high (green) to low (red) difference so that it is easier visually to find those parameters which have greater mean difference between good and bad runs. The parameters closer to green are those which the outcome is most sensitive, and should therefore be included in the OEC. From table above, the parameters which will be included in the OEC are Velocity and Rotational Velocity. Along with these inputs, the % environment explored and absolute velocity deviation are included, as output variables which denote successful runs. The OEC is shown below in Equation 3, where variables with a “+” denote the mean of good runs for that variable.

$$OEC = \sqrt{\left(\frac{Vel - \overline{Vel_+}}{\overline{Vel_+}}\right)^2 + \left(\frac{RotVel - \overline{RotVel_+}}{\overline{RotVel_+}}\right)^2 + \left(\frac{\%Explored - 100\%}{100\%}\right)^2 + Abs.Vel.Dev.}$$

Equation 3: Overall Evaluation Criterion

Each term contained within the OEC is small when the vehicle has inputs close to those that are performing the best in simulation, explores more of the environment, or deviates only slightly from the input velocity.

As shown above, the USARSim environment has the capability to provide critical insight to the relationship between physical and software characteristics with their effectiveness at performing a particular mission. By varying physical characteristics such as battery life, motor power, and vehicle dimensions along with software characteristics such as the wall-following and safety parameters, the higher-fidelity USARSim environment can facilitate quantitative analysis on how all the functioning parts of a vehicle affects its mission effectiveness. The ASDL MAST team expects that insights gained will become only more useful with increased simulation fidelity, however even from the test cases analyzed above, lessons such as cut and run, deploy closer rather than farther to the recon site, and never slow down can be extracted and applied to the development of a vehicle for the mission.

1.5. Development of Experimental Physical Quad rotor and Validation of M&S Environment

An experimental prototype quad-rotor was developed to serve as a test bed for evaluation of various autonomy algorithms and tactics, and for validation of the higher-fidelity modeling and simulation environment. It is capable of autonomous flight, which at current development stage includes automatic take-off, altitude hold, and full operational obstacle avoidance. Currently, Robotic Operating System (ROS) and CoreSLAM are being implemented onto the quad-rotor to enable fully autonomous flight and mapping capabilities. The ROS/CoreSLAM has been successfully implemented and tested on a Linux machine Gazebo simulator and ranging LIDAR. The final product is expected in near future. The current configuration is shown in Figure 17: Quad-rotor.

Figure 17: Quad-rotor

The quad-rotor is based on a commercially available platform known as ArduCopter. It utilizes the ArduPilot Mega (APM) board to provide stability, with the help from an IMU and an ATMega microcontroller. However, the platform has been drastically modified with to customize it for ASDL's MAST effort. Most of the structural components have been redesigned from scratch to accommodate added controller board and sensors. It is equipped with a sonar, for altitude hold, a ranging LIDAR sensor, for obstacle and navigation, and a wireless communication device for external processing.

To achieve autonomous flight a secondary board was added to the vehicle, which required restructuring of the air frame as mentioned above. This board, the PandaBoard, is outfitted with an OMAP4 processor (the successor to the GumStix's OMAP3). The PandaBoard takes laser ranging data from the LIDAR and IMU data from ArduCopter's stability system, the APM, to perform navigation. Another major component needed for autonomous flight is a communication link between the PandaBoard and the ArduCopter's APM. The APM's firmware was modified to transmit IMU data and system diagnostic data to the PandaBoard over a serial data link. The APM was also modified to allow it to accept guidance commands (forward, backwards, left, right, etc.) from PandaBoard over the same serial link. Software has been developed for the PandaBoard to gather the IMU and diagnostic data from the APM, while simultaneously sending guidance commands. Recently, the architecture that links the Ardu-Pilot Mega (APM) board, which controls the poise (attitude stability) and movement of the vehicle, and the PandaBoard, which interprets incoming sensor data into commands for the APM, has been greatly improved. It has moved in a modular direction, allowing control commands to come from a variety of sources. This helps immensely in testing as it is easy to switch between control algorithms and control sources in real time. The APM and the PandaBoard still communicate over a serial port. A single process on the PandaBoard watches this port for telemetry data and redirects it to a TCP port over the wireless to a ground control station. This same process also listens to a UDP port where it waits for attitude and altitude commands. The controlling process only needs to send packets to this UDP port to establish control over the vehicle. The controlling process tends to run on the PandaBoard communicating over the loopback address, but it can be run off-board if needed, usually for diagnostic purposes. The current implementation of the onboard control take laser scan data from the Hokuyo laser scanner and uses it to avoid walls and obstacles by trying to maintain a certain separation distance. For off-board control, a simple process can take input from a joystick or keyboard and relay those commands over a wireless connection allowing for user based control. The control processes can be enabled and disabled on without any other interaction with the platform allowing for quick turnaround time for code debugging, compilation, and re-initialization. With a working navigation algorithm in place the vehicle is able to perform fully autonomous flight. Once the implementation of SLAM via ROS/CoreSLAM is completed, the quad-rotor will be capable of performing complete autonomous missions already being performed in the M&S environment, allowing for validation of the simulation.

The developed quad-rotor is of similar type and equipped with the same sensors as the vehicles used in modeling & simulation and thus effectively serve as real-world validation, when used in the same scenario and map. In order to compare results in-house, new environments in higher fidelity M&S have been constructed from measurements of the Weber building (Georgia Tech). The last step in order to quantify the operational disconnect and technology gap is to utilize the quad-rotor to first validate the modeling and simulation environments as described above and then to run virtual experiments in the M&S by varying performance parameters. The validation of M&S is planned to be achieved by running same mission scenarios with same quad-rotor and sensors virtually and physically.

Once validated, the next step will be to vary the physical experiments in a virtual environment, such as adjusting the maximum velocity or battery life of the vehicle. These variations which allow the vehicle to perform a mission and better identify gaps in the capability necessary in a physical platform. In this manner, simulation (forming a closed loop with physical experimentation) can be used to identify platform areas in need of further development, by giving the simulated vehicle unrealistic characteristics that allow it to perform the mission more effectively than state-of-the-art.

1.6. Development of Experimental Test Equipment and Physics Based Analysis Tools

Several other branched out efforts for MAST are currently underway to support ASDL's MAST research. In addition to advancements in the overall gap analysis environment, further work is being done to build a preliminary analysis tool for the design of complex flapping wing systems. To determine the most appropriate wing topology and kinematics for Flapping Wing Micro-Aerial Vehicles (FWMAVs) in a given mission, a deeper understanding on the effects of wing shape, venation, and kinematic wing-vehicle interactions is needed. Multi-Body Dynamics (MBDyn) open source software is used to model flapping wing configurations and simulate simple flapping wing excitations, allowing for higher fidelity in both the agent base modeling and sizing and synthesis codes.

To validate the MBDyn model, test cases for rectangular, Locust, Balsa, and Drosphila wings, with zero, one, and two spars, will be compared with experimental results from further research both within ADSL and the greater MAST Consortium. Then, the overall modeling and simulation environment must be verified and validated using a replica vehicle model. To analyze a model vehicles performance, parameters of interest, such as force, must be physically tested. The thrust and lift generated by the quad rotor and other MAST vehicles will be measured using a custom built load cell. These results, in conjunction with MBDyn models, will be used to validate the accuracy of the simulation environment. Details are given in the following sections.

1.6.1. Physical Lift and Thrust Measurements

To determine the accuracy of the modeling and simulation environment, the results of the computation DoE have to be validated with a physical vehicle's performance. To analyze a vehicles performance parameters of interest, such as force, must be physically tested. The thrust and lift generated by the quad-rotor and other MAST vehicles will be measured using a custom built load cell. While COTS load cells are available, they are expensive and generic, which can make mounting impossible. There are also a variety of resolutions that a load cell can resolve to, and being able to resolve small forces (micro-vehicles may produce anywhere from 0.1 to 200 grams) requires a sensitive and costly design. A custom-made load cell, however, is designed to measure the thrust, lift, and moments in the range of interest and fit the vehicle appropriately. Having design freedom also means being able to avoid resonant frequencies that may affect performance results, resulting in a more effective product at literally a fraction of the cost.

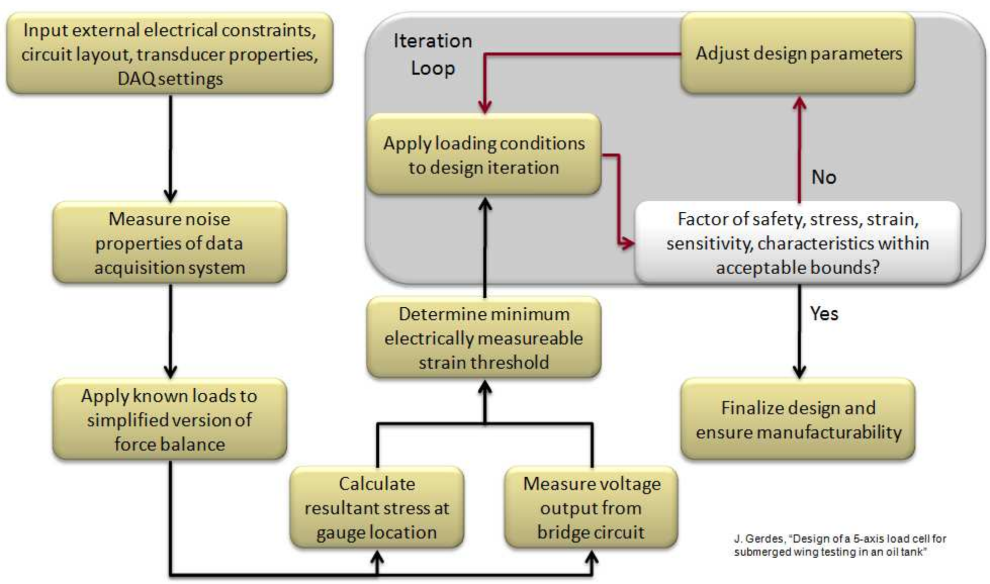

Figure 18: Load Cell Design Process

The design process is relatively simple and is based on an iterative design loop, as shown in Figure 18. After manufacturing the design, it will be fitted with a series of strain gauges arranged in Wheatstone bridge circuits. When a force is applied to the cell, the material experiences strain, causing the legs of the Wheatstone bridge to be unbalanced and the resulting voltages can be measured with a data acquisition system. The equation for engineering strain is shown in Equation 4, where ε is the engineering strain, L0 the initial length, and L1 the final length.

$$\varepsilon = \frac{(L_1 - L_0)}{L_0}$$

Equation 4

Piezo-resistive semiconductor strain gauges are ideal for small applications because they measure only 0.008” wide and have high sensitivity, more than 50 times greater than that of foil gauges. However due to the high changes in gauge resistance, care must be taken when using semiconductor gauges with the Wheatstone bridge. The full bridge was chosen since it has improved linearity by mitigating the temperature affects generally seen when using piezo-resistive strain gauges. For larger applications, regular foil gauges are acceptable and require much less precision during application. The Wheatstone bridge is characterized by Equation 5 and the strain measurement from the Wheatstone bridge circuit is shown by Equation 6 and is dependent on the gauge factor (GF).

$$V_{out} = V_{in}\left[\frac{R_4}{R_4 + R_2} - \frac{R_3}{R_1 + R_3}\right]$$

Equation 5

$$\varepsilon = {\frac{\Delta R_2}{R_2}}\Big/_{GF}$$

Equation 6

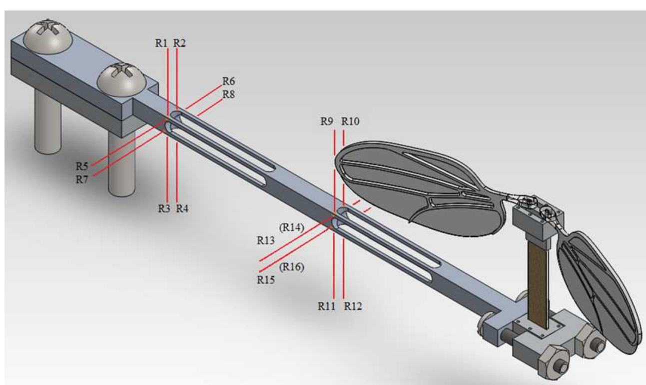

Figure 19: Custom Built Load Cell for Flapping Wing

Figure 19 shows an example of an ARL custom built load cell that is designed to measure lift, thrust, and pitching moment of a flapping wing vehicle to 0.1 grams. The gauges are located in red and make up four full bridge circuits. After calibrating the cell with known masses, the micro-vehicle is attached and force data is obtained. The final design features create a balance between system sensitivity and stiffness. The system must have adequate sensitivity to resolve small forces, but enough stiffness to avoid low natural frequencies near those generated by a flying micro-vehicle.

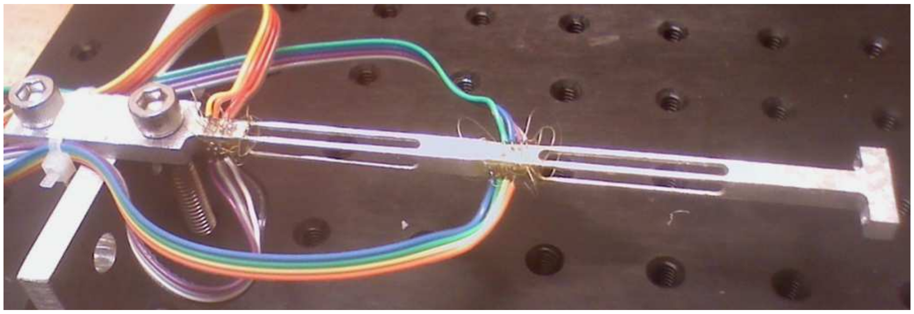

Figure 20: Finished ARL Load Cell

The MAST team would like to build a higher fidelity load cell based on the model above capable of resolving forces in all 6 axes (this is necessary for designs that may see yawing moments, such as the quad-rotor). Ideally, the design would be sensitive enough to resolve forces as small as 10 grams and up to 200 grams without damaging the load cell, although this may result in designing two separate load cells or an adjustable design. The cell will determine forces generated by the MAST systems to a much higher resolution than the current "scale and mass" system and be much more cost-effective than testing on a wind tunnel balance.

This load cell will be able to gain force measurements for a variety of vehicle designs, which will be used to validate the modeling and simulation environment. The flow chart in Figure 21 shows how the load cell experiments fit into validating computational models.

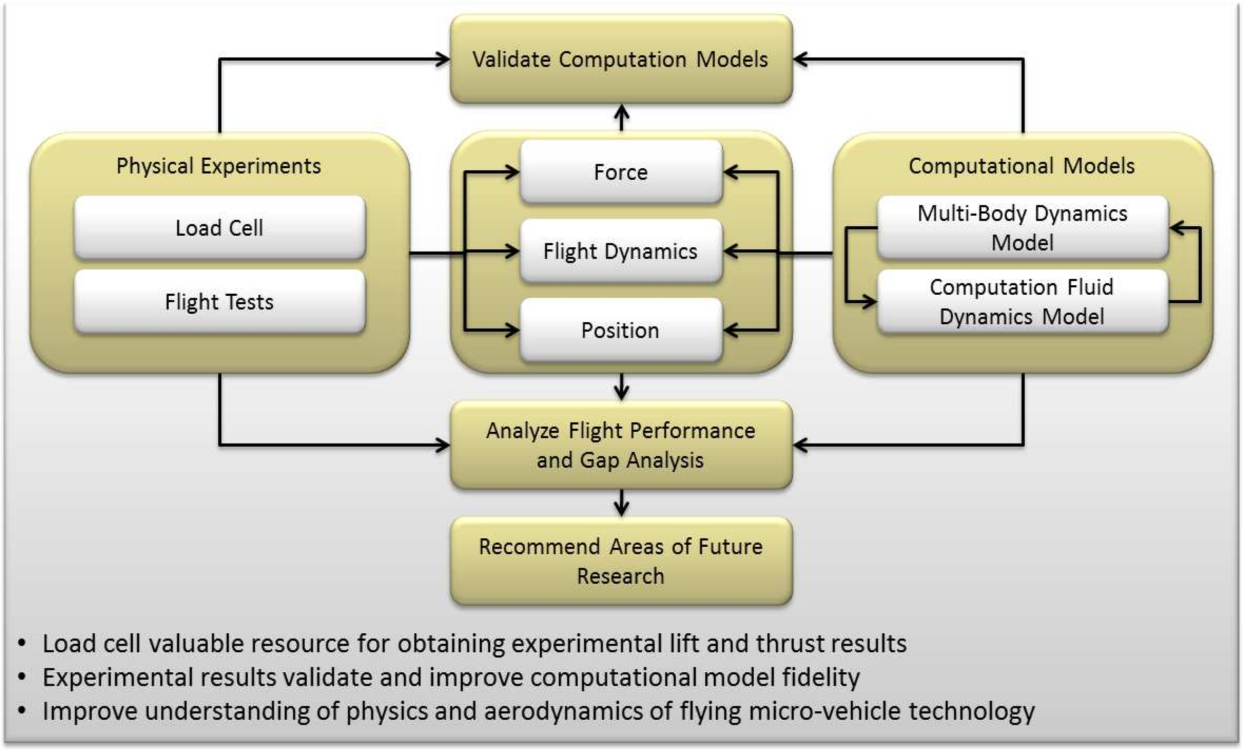

Figure 21: Validation of Computational Models using Physical Experiments

1.6.2. Multi-Body Dynamics Analysis

Since the physical flapping wing testing can be time consuming, a simulation model is also used to test wing configurations and kinematics. Multi Body Dynamics (MBDyn) is used to model complex wing topologies and simulate their response to combination of wing kinematics such as stroke amplitude, angle of attack, wing rotation, and wing deformation that in turn determine the complexity of maneuverability in translational, hover, gliding, and rotation motion of these flapping wing vehicles.

Flapping wing topology in biological systems, such as sweep, aspect ratio, shape, and venation play an important role in the aerodynamic performance and structural behavior of the wings. Thousands of years of natural selection have fine-tuned these variables for the flight and maneuver capabilities of such species necessary for survival. Therefore, to design wings for flapping wing vehicles that meet a given set of requirements, a preliminary design study needs to take place that incorporates such wing kinematics, topologies, and expected flying conditions. MBDyn is a good way to go about modeling complex wing topologies with certain degree of complexity and simulate their response to prescribed kinematics.

The wing structures in MBDyn can be modeled using a combination of beam elements and shell elements. The beam element is modeled by means of an original Finite Volume approach, which computes the internal forces as functions of the straining of the reference line and orientation at selected points along the line at evaluation points. At each evaluation point, a 6-dimensional constitutive law is defined, which is used to calculate the relationship between strains, the curvatures of the beam and their derivatives and internal forces and moments. The wing venation is modeled as a series of 1-dimensional beams. The shell elements are used to model the membrane of the wing. Only linear elastic constitutive properties can be currently modeled using the shell element method. The constitutive law consists of a matrix that represents the force and moment fluxes as functions of linear and angular strains.

For validation of the MBDyn model, a flat plate wing structure will be modeled and subjected to a clamp boundary condition at one end, and a vertical concentrated oscillatory sinusoidal force at the other end. The natural frequency of a flat plate can be calculated using Rayleigh's method that is based on trigonometric and polynomial approximations of the mode shapes of the plate under certain boundary conditions. For this analysis, the flat plate was clamped at one end, and free from the rest of the edges, as shown in Figure 22: Flat plate boundary conditions, with span a, width b, and thickness t.

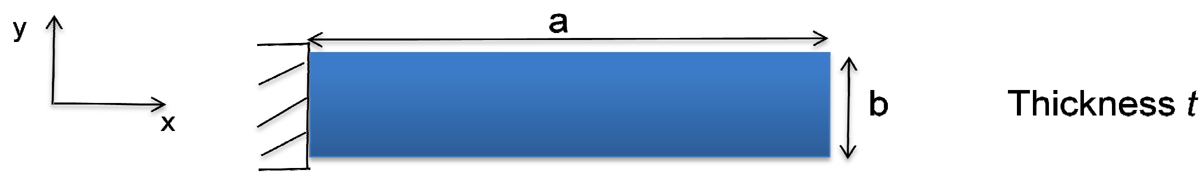

Figure 22: Flat plate boundary conditions

The assumed mode shape for this boundary condition is given by:

$$Z = Z_0\left(1 - \cos\left(\frac{\pi x}{2a}\right)\right)$$

Equation 7

This boundary condition satisfies both the boundary conditions at the clamped and the free ends.
The strain energy is given by the area integral of the second derivative of the mode shape:

$$V = \frac{D}{2}\int_0^a \int_0^b \left(\frac{\partial^2 Z}{\partial x^2}\right) dydx$$

Equation 8

Where D is the stiffness factor, and is given by:

$$D = \frac{Et^3}{12(1-\mu^2)}$$

Equation 9

Where μ is Poisson's ratio and E is Young's modulus. The kinetic energy is given by the following expression:

$$T = \frac{\rho\Omega^2}{2}\int_0^a\int_0^b Z^2 dydx$$

Equation 10

Where ρ is the material area density and Ω is the frequency of oscillation in radians per second. Assuming no energy dissipation, the strain energy is equal to the kinetic energy:

$$V = T$$

Equation 11

Solving for the frequency of oscillation gives the natural frequency of the flat plate for this particular mode shape, which is given by:

$$f_n = \frac{0.56}{a^2}\sqrt{\frac{D}{\rho}}$$

Equation 12

This natural frequency is the frequency that the tip displacement is the largest. Therefore, validations occur by modeling this wing structure and boundary conditions in MBDyn, and vary the natural frequency of the oscillation and measure the wing tip displacement. The maximum wing tip displacement should occur at an oscillating frequency close to the theoretical natural frequency.

Once the MBDyn model approach can be validated, the complex wing structures will be modeled and simulated to study their response to given set of wing kinematics. Wing topologies will be modeled after experimental wing shapes with existing data. Displacements and structural behavior will be compared to experimental data for further validation. Once this validation takes place, the studies will be automated to analyze the effects of different variables in wing structures such as sing shape, venation, membrane material, and input kinematics. This in turn will provide an understanding of the effects of these variables on the structural behavior of flapping wings that is crucial for the design of flapping wing vehicles.

1.7. Development of Integrated Physics based Sizing & Synthesis of Micro Aerial Vehicles Environment

Flapping-wing Micro-Aerial vehicles are biologically inspired systems being studied and developed by the Vehicles Technology Directorate (VTD) of the Army Research Laboratory (ARL) for important applications in the warfare environment. The Defense Advanced Research Projects Agency (DARPA) has defined these micro aerial vehicles as having maximum dimensions of less than fifteen centimeters. Their size, capability and agility make them potential candidates for a number of mission scenarios and applications such as surveillance platforms that enhance the Warfighter's capabilities and safety in a hostile and unknown environment. These vehicles, along with other MAVs being developed at VTD, are equipped with state of the art cutting-edge technologies also being created in consortium with the VTD effort. This in turn opens up the design space further than the physical design and configuration alone. The understanding of the effects of the new technology and capability on the size, configuration and performance of the vehicle need to be understood to a certain degree to determine any gaps that need to be addressed.

These flapping wing vehicles have the benefit of reduced aerodynamic power required, combined functionality of propulsion and controls, static thrust and hover capabilities, as well as increased maneuverability. However, these vehicles are not very well understood yet. Over the years, researchers have focused on the development of models to understand the physics and functions of the flapping wing species, and with this understanding they go further to develop similar systems that accomplish similar goals. One portion of research has been in scaling electrical components such as computers, motors, and batteries while improving component performance. This thrust has provided many advances such as communication methods and antennas, sensing, power, and cooperative control. But many of these systems are being developed independently, without a very clear connection to the effect of this particular system on the overall vehicle system. Therefore, a platform such as a FW-S&S could facilitate this integration to study the effects of individual systems on the overall size, configuration, and performance of the vehicle through sensitivity analysis and other methods.

A Flapping-wing Sizing and Synthesis (FW-S&S) tool has been developed and is used to size biological inspired flapping wing vehicle configurations. The layout of this tool is shown in Figure 23: FW-S&S Tool Layout. The inputs to this sizing tool are simulation performance metrics such as time of flight, velocity, and payload weight, environment metrics in terms of altitude, configuration metrics such as span, aspect ratio, and flapping frequency and amplitude, and power efficiency metrics such as battery energy density and figures of merit at different flight conditions.

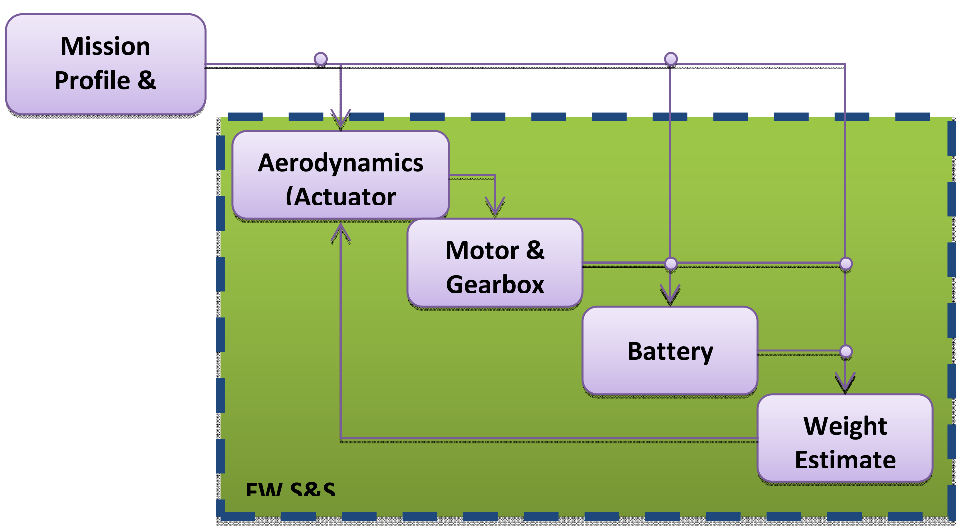

Figure 23: FW-S&S Tool Layout

Flapping-wing aerodynamics is a complex phenomenon involving highly unsteady events such as vortex shedding and capture, low Reynolds number, and wing kinematic effects. Aerodynamic performance is highly dependent on these elements, but they can be difficult to model. Full aerodynamic modeling is not the scope of this study; therefore a low fidelity aerodynamic model is used instead. The FW-S&S tool uses a simple partial actuator disk method to calculate the aerodynamic power required for flight with the assumptions of one-dimensional, quasi-steady, incompressible, and inviscid flow. This method was presented by Shkarayev and Silin in 2010.

Once the power required for flight is determined, this power plus the power consumed by the payload (i.e., sensors, processing, and other technologies), should be provided by stored energy in the form of batteries. Energy scavenging methods are not being modeled yet in this study. The power system is modeled using a brushless DC motor, transmission, and speed controller, with power supplied by a battery system. A catalog of commercial motors was used to create parametric relationships for the motor parameters as a function of required power, while filtering configurations not applicable to this study (such as motors with diameters greater than 22 mm). A mechanism is assumed to transfer the rotary motion of the motor to an oscillating flapping motion for the wings in terms of frequency and amplitude. A transmission is sometimes needed when the flapping frequency is significantly below the motor operating speed. Speed controllers are also used to provide DC power signals to multiphase windings in a brushless DC motor causing the motor to generate torque. The response surface equations are represented with polynomials of first and second orders, and logarithmic functions, with interaction terms. The discrete nature of the data from the catalog leads to some relative error in the modeling, but the resulting representative fits are good approximations at this level of fidelity for this study.

A specific energy-based sizing is used for sizing the battery. The required energy for a battery system is obtained by multiplying the mission profile time by the power requirements for each phase in the mission. Battery mass is determined using a specific energy associated with the battery. The minimum battery voltage is defined by the motor requirements and payload characteristics. With a defined voltage per cell, the battery back cell count can be determined. This voltage may then be stepped down to operating voltages for motors, payload, and other loads. For this study, it is assumed that battery voltage is driven by the motor requirements and not payload voltages.

The mission profile is specified in terms of time of flight and speed of the vehicle. The outputs are sizing characteristics of the flapping wing vehicle such as total system weight, power system mass fraction, payload mass fraction, and structural mass fraction. Determining remaining structural elements is accomplished by use of a mass fraction on the total mass estimate in an iterative process.

1.7.1. Validation Tests

To validate the FW-S&S tool using real world systems, this tool was tested with parameters commercially available for different flapping-wing vehicles. One example is the hummingbird-like nano air vehicle by AeroVironment, Inc., which is capable of fully controlled flight. Another example is the 15 cm wing span flapping wing vehicle from Konkuk University, which is used to test the material of the wing in a wind tunnel. Next is the DelFly II by DelFly Micro-Aerial Vehicles from the Technical Institute of

Delft, which can fly horizontally at a relatively high speed of 15 m/s while carrying an onboard camera. The inputs for each of these vehicles are shown in Table 4. Some of these values had to be assumed with educated guess since this information could not be determined from the different sources.

Table 4: Flapping Wing Vehicles and Inputs

Inputs	AV Hummingbird	Konkuk University	DelFly II
Altitude (m)	0	0	0
Time of Flight (min)	11	1	5
Time Idle (min)	2	0	0
Velocity (m/s)	5	2	10
Payload Wt (g)	5	0	1.62
Payload Power (W)	0.5	0	0.3
Wing Span (cm)	16	15	28
Wing AR	4	2.65	3.5
Flap Amplitude (degrees)	170	45	48
Flap Frequency (Hz)	40	30	14
Wing Area Density (g/m^2)	30	10	7
Structural Wt Fraction	0.3	0.3	0.5
Mechanism Efficiency	0.6	0.6	0.6
Figure of Merit	0.6	0.6	0.6
Battery Specific Energy (MJ/kg)	0.9	0.72	0.9

The results of the validation tests are shown in Table 5 in terms of the total weight of the system calculated from the model, and given by the different sources. Some of the results from the sizing tool model deviate by a large amount from the actual size due to the type of motors used being different from the general trend in the catalog used for our tool, and the assumptions used for some of the values which were not provided by the sources. A larger difference is seen with systems at the lower end of total system weight. This is mainly due to the fitting inaccuracy when the motors and gears need to be scaled down. For vehicles in the range of 15 to 20 grams, using standard power system configuration and structure materials, the model predictions are relatively good enough at this level of fidelity.

Table 5: Results from Applicability Tests

FW Vehicle	Total Mass (g)	S&S Calculated Mass (g)	% Difference
AV Hummingbird	19	19.8	4.0
Konkuk University	8.7	10.1	15.1
DelFly II	17	16.3	4.3

1.7.1. Sensitivity Analysis

A sensitivity analysis was done to explore the preliminary design space. The input metrics were varied and the flapping wing vehicle system size was calculated. A DoE was used to vary the inputs metrics with the minimum number of evaluations needed while still getting good amount of information about the design space. Although the input variables are continuous in nature, a ‘discretized’ set of 5 levels on each variable would require almost two hundred years evaluating with an average time of 0.2 seconds if the space is explored without the DOE method. Even reducing to three levels on each input variable would require over a month of evaluation time.

Three types of DOEs were used in parallel to explore the design space as complete as possible. The first DOE is a D-optimal design to provide good overall examination, particularly focused on the edges of the design space. The second is a space-filling DOE, called Latin hypercube space filling design, which is used particularly to examine the interior of the design space. Finally, random cases DOEs are included to further fill the design space with additional data and provide a measure of the goodness of fit. These cases are created using the SAS software in JMP. Table 6: DOE Types and Number of Cases shows the DOEs and the number of cases.

Table 6: DOE Types and Number of Cases

DOE Type	Number of Cases
D-Optimal	32
Latin Hypercube	30
Random	800
Total	862

Each of the cases for the different DOEs used a value chosen within each of the corresponding input variable range. These input variable ranges were chosen from educated guess on limitations for MAV vehicles. Table 7 shows the ranges for the input variables.

Table 7: DOE Input Variable Ranges

Input Variable	Minimum Value	Maximum Value
Altitude (m)	0	6000
Flight Time (min)	5	20
Idle Time (min)	1	5
Flight Speed (m/s)	0	10
Payload Mass (g)	1	200
Payload Power (W)	0.5	5
Wing Span (cm)	5	30
Wing Aspect Ratio	2	6
Flap Amplitude (deg)	30	170
Flap Frequency (Hz)	5	75
Wing Area Density (g/m^2)	20	50
Structural Weight Fraction	0.2	0.6
Flap Mechanism Efficiency	0.3	0.6
Figure of Merit	0.3	0.6
Battery Specific Energy (MJ/kg)	0.1	1

A meta-model fitting to the design points created using response surface equations (RSEs) allows for a factor sensitivity analysis, where factors are referring to the input variables. This allows understanding the relationship between factors and the size of the vehicle, and which factor affect the vehicle system size the most.

Second order models on the data showed poor fits; therefore the second order models were created using a logarithmic transformation for most of the RSEs. These transformations were applied to every response, except on the RSE for payload mass fraction and motor and gearbox efficiency which showed larger fit errors with the logarithmic transformation. Each of these regressions fit reasonably well in an R^2 sense, however model fit error and model representation error remained somewhat high, which means that further refinement of the data should be investigated. Higher order terms for the models were attempted. In some cases these higher order models did improve the agreement with the data, but in some instances at the cost of over-fitting the data. Therefore, to avoid these problems, and for the scope of this study at point, the second order models were kept. Reducing model variability and the errors may be a focus of future work.

The sensitivity analysis is done by looking at the effects of the input factors on the system responses from the RSEs created. These effects can be presented in pareto plots which show the magnitude and the direction of a factor impact on a given response. Figure 24 shows the pareto plot for the total flapping-wing vehicle system weight. As can be seen in the figure, payload weight and battery specific energy are dominating factors for the total weight of the system.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Payload Weight*Payload Weight	-5.842e-5	1.655e-6	-35.30	<.0001*
Payload Weight	0.0240094	0.001044	22.99	<.0001*
Battery Specific Energy*Battery Specific Energy	1.1584715	0.081051	14.29	<.0001*
Payload Weight*Battery Specific Energy	0.0030545	0.000338	9.03	<.0001*
Time of Flight*Battery Specific Energy	-0.034347	0.004395	-7.81	<.0001*
Wing Span*Wing Span	0.0008435	0.000112	7.54	<.0001*
Battery Specific Energy	-1.60485	0.236689	-6.78	<.0001*
Speed*Payload Weight	-0.000183	2.963e-5	-6.18	<.0001*
Time of Flight	0.0780133	0.013893	5.62	<.0001*
Payload Weight*Payload Power	-0.000359	6.757e-5	-5.31	<.0001*
Structure Weight Fraction*Structure Weight Fraction	2.1239166	0.414347	5.13	<.0001*
Wing Span	-0.048512	0.009508	-5.10	<.0001*

Figure 24: Pareto Plot of Factor Effects to Total System Weight

Factor sensitivity can also be analyzed with the use of a prediction profiler. Figure 4 shows the prediction profiler for the total system weight. Each blue line shows a partial derivative of the response at a point of interest. As can be seen in Figure 25, payload weight and structure fraction have a significant effect on the total weight of the system. Since the prediction profiler shows the effect of the different factors on the response at a given point, this point, defined by the red dashed line, must be changed manually to understand the larger space.

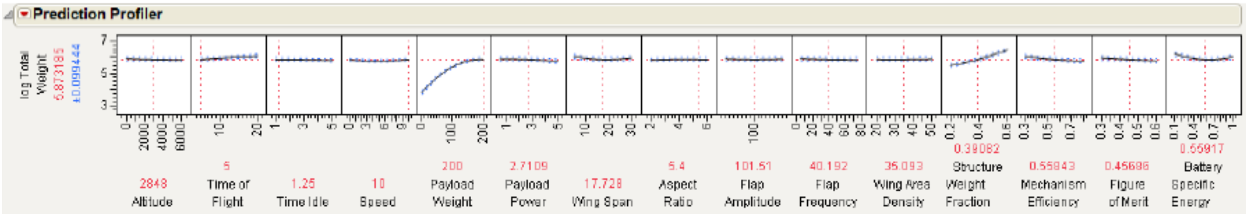

Figure 25: Prediction Profiler of Factor Effects to Total System Weight

The same sensitivity analysis can be made to the effects of the factors on other responses. Figure 26 shows a composite prediction profile for different responses of interest at given design points.

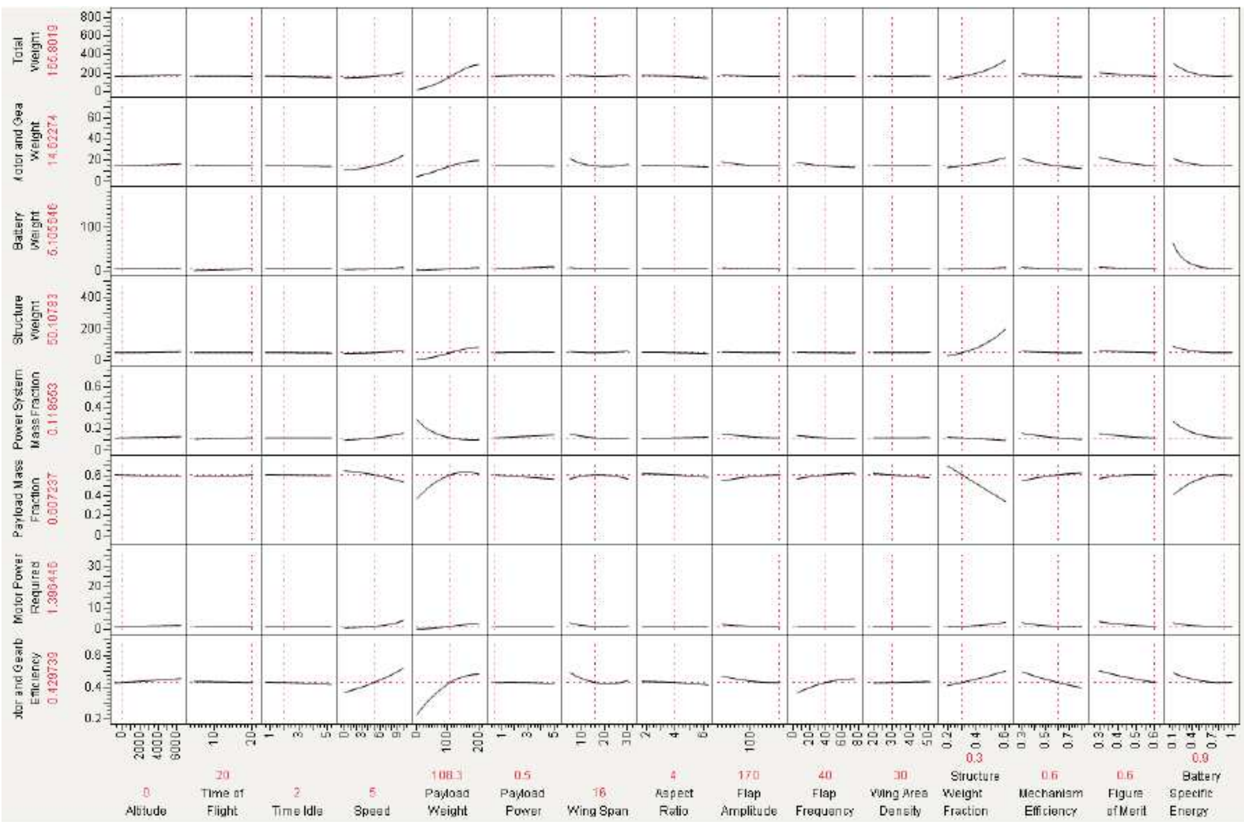

Figure 26: Composite Prediction Profile for Complete Sensitivity Analysis

The complete prediction profiler shows several overall system characteristics and trends that are important for the design of flapping wing vehicles. Notably, for small vehicles, a large mass fraction is desired to use space and mass more efficient. Improved portability for small vehicle should also benefit the user by reducing equipment loads and space requirements. Some of the major trends observed were that payload mass, followed by structure weight and battery specific energy, have a great effect on most components of the design, especially for smaller vehicles.

Somewhat strangely, time of flight has a relatively weak impact on the total weight of the system using the ranges chosen. Instead, battery sizing is more heavily influenced by instantaneous power needs from the payload. This in turn caused aerodynamic and overall mass factors to drive battery sizing. High specific energy reduces the sensitiveness of battery sizing from all other factors.

At small sizes, power requirements remain relatively stable. Mechanism efficiency is the strongest driver at small sized since this simply scales the power required. Of secondary importance is the flight speed and, which leads to major effects on power required up to 5 times larger with a 10 m/s increase. Flapping amplitude also increases power required several multiples in the lower amplitude range.

At larger sizes, power is affected heavily by many factors as total system weight is. Wing span for example begins to play a major role, with small wings requiring significantly more power. Also, increases in flap frequency reduce the overall power required.

1.7.2. Remarks and Future Work

The S&S tool for flapping wing vehicles is an effort to learn more about the design space of these new biologically inspired systems. As better technologies emerge, and more important system input factors are identified, this S&S is being upgraded carefully while trying to keep the low fidelity design analysis at this preliminary stage of the design process. While being a low fidelity model, it will provide useful information about system characteristics that are crucial for the design of such vehicles. As this tool becomes more applicable, the methods used to calculate required power and structure weight will become more sophisticated, and therefore the model will be more accurate.

1.7.3. Rotorcraft Sizing and Synthesis (RC-S&S) Tool

S&S tool for rotorcraft vehicles is used to size vehicles with different rotor configurations which include coaxial helicopters, small helicopters, and quad-rotors. A layout of the tool is shown in Figure 27, which is similar to the FW-S&S tool layout, with a different method of calculating the aerodynamics of the vehicle. The inputs to this sizing tool are simulation performance metrics such as time of flight, velocity, and payload weight, environment metrics in terms of air density and ground altitude, and configuration metrics such as number of rotors, motors, wings, and locations of each. The tool uses blade element method to calculate the forces and moments necessary to trim the vehicle at different flying conditions, and calculates the power required to do so and perform the performance metrics. The power system is also modeled using a brushless DC motor, transmission, and speed controllers for each or combination of rotors, with power supplied by a battery system. The specifications of these power components are also chosen from data fits on supplier’s catalogs available today, based on the power required for trimming the vehicle and performing its tasks, and the power consumption from the payload (such as sensors, and other technologies). The outputs are sizing characteristics of the rotorcraft vehicle including total system weight, component’s weight, number of cells required, gear-motor configuration, structural weight, and payload mass fraction.

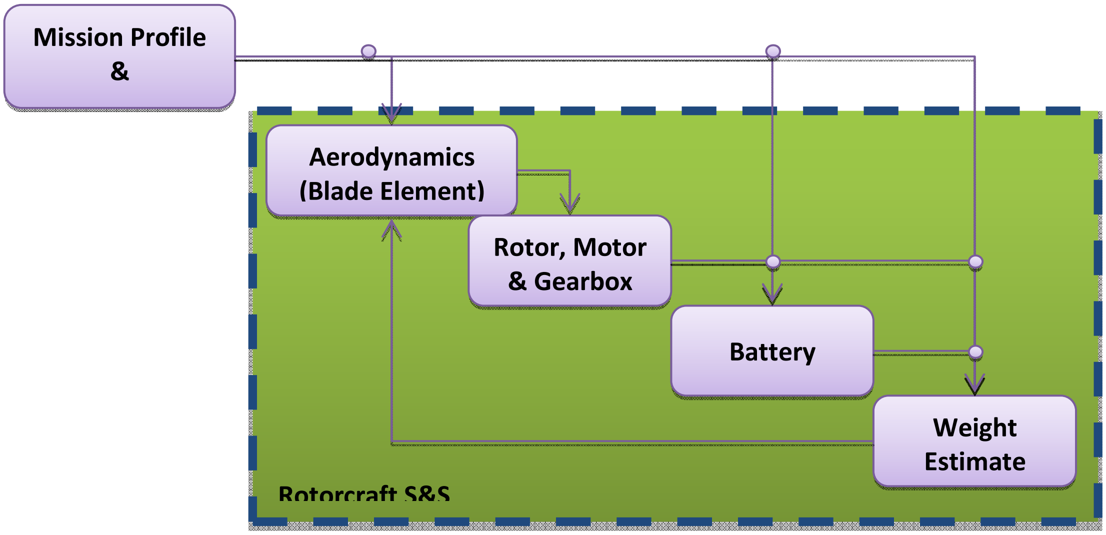

Figure 27: Rotorcraft S&S tool

1.7.4. Validation Tests

To test the applicability of the RC-S&S tool, the tool was applied to vehicles of known characteristics. One case is the quad-rotor that is used for physical testing in the lab. The physical dimensions of the vehicle are shown in Figure 28.

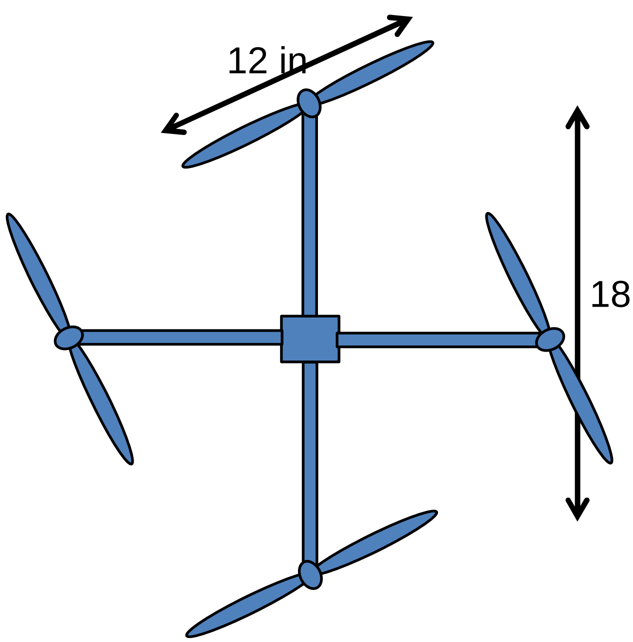

Figure 28: Quad-rotor Physical Dimensions

The structural weight of the quad-rotor is 2.6 lb. It is equipped with motors, speed controllers, rotors, and sensors that together compose the payload weight. The sensors are concentrated at the center of the quad-rotor. The breakdown of the payload weight is shown in Table 8.

Table 8: Quad-rotor Payload Weight Breakdown

Component	Weight/Item (lb)	Quantity	Total Weight (lb)
j-Drones A-2830/12 850 kV Motor	0.14	4	0.56
GEMFAN 12x4.5, 12 in span rotors	0.02	4	0.08
HOKUYO URG LIDAR	0.35	1	0.35
Zippy Li-Po 2650 30C Battery Pack	0.51	1	0.51
		TOTAL	**1.5**

Another case is the commercially available MicroDrone md4-1000 by microdrones, which is used for aerial video, inspection, and surveillance. The input variables for both of these quad-rotors are shown in Table 9.

Table 9: Input Variables for Quad-rotors

Inputs	ASDL Quad	MicroDrone md4-200
Forward Speed (ft/s)	33.8	27
ROC (ft/min)	30	30
Distance Range (miles)	2.3	0.31
Lateral Speed (ft/s)	20	16
Time (min)	20	30
Num_rotors	4	4
Num_motors	4	4
Num_xmsn	4	4
Payload current cons. (mA)	2	1
Structural Weight (lb)	2.6	1.76
Structural Weight Fraction	0.6	0.8
Payload Weight (lb)	1.5	0.44

Table 10 shows the actual weights of the vehicles, the results from the RC-S&S tool, and the percent difference between the two values. As can be seen, the percentage difference is relatively low for both of the cases used. With these two cases under these ranges, the applicability of the RC-S&S tool shows good-enough results considering the low fidelity models that are used.

Table 10: Results of Validation Tests

Vehicle	Total Weight (lb)	S&S Calculated Weight (lb)	% Difference
ASDL Quad-rotor	3.6	3.7	2.7
MicroDrone md4-200	2.2	2.2	0

1.7.5. Sensitivity Analysis

A sensitivity analysis was done to explore the preliminary design space of quad-rotors. The input metrics were varied and the rotorcraft vehicle system size was calculated. A Design of Experiments (DOE) was used to vary the inputs metrics with the minimum number of evaluations needed while still getting good amount of information about the design space.

The DOE used is a space-filling DOE, called Latin Hypercube space filling design, which is used particularly to examine the interior of the design space. These cases are created using the SAS software in JMP.

Each of the cases for the different DOEs used a value chosen within each of the corresponding input variable range. These input variable ranges were chosen from educated guess on limitations for quad-rotor vehicles. Table 11 shows the ranges for the input variables.

Table 11: DOE Input Variable Ranges

Input Variable	Minimum Value	Maximum Value
Forward Speed (ft/s)	8.4	33.8
Rate of Climb (ft/min)	0	3
Distance Range (miles)	0.23	1.2
Lateral Speed (ft/s)	0	8.4
Time (min)	5	10
Payload Current Consumption (mA)	0.5	1
Structural Weight (lb)	0.2	1
Structural Weight Fraction	0.3	0.7
Payload Weight (lb)	0.3	1

Second order models on the data showed good fits. Each of these regressions fit reasonably well in an R^2 sense, however model fit error and model representation error remained somewhat high, which means that further refinement of the data should be investigated. Reducing model variability and the errors may be a focus of future work.

Figure 29 to Figure 32 show the Pareto plots for the gross weight, structure weight, battery weight, and horse power required, respectively.

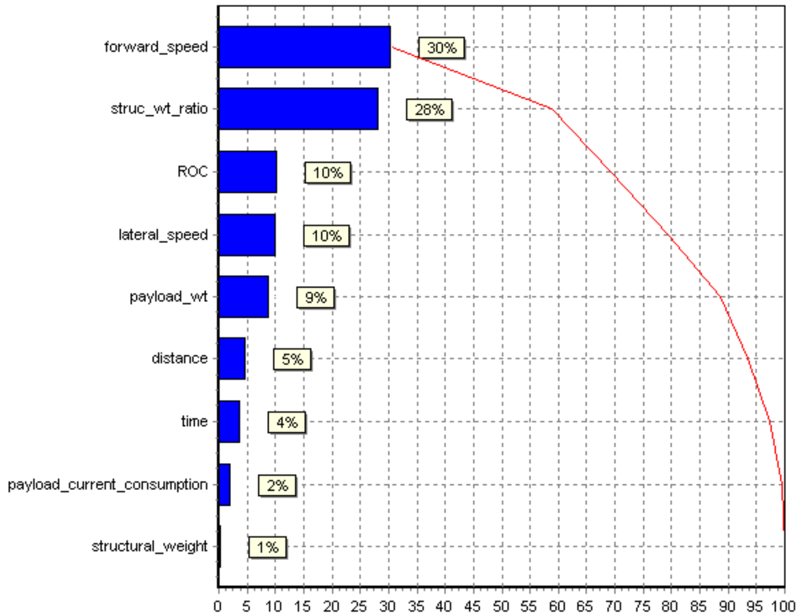

Figure 29: Pareto Plot of Factor Effects to Gross Weight

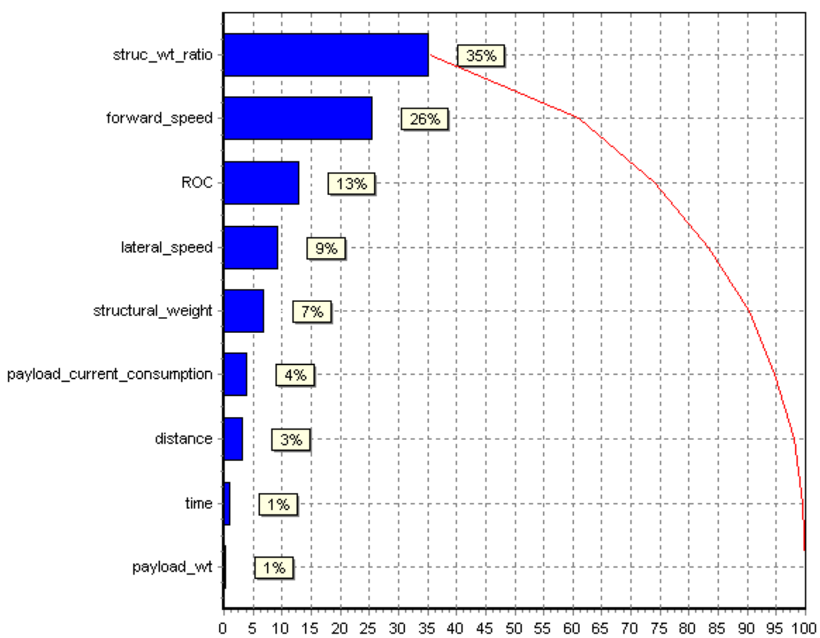

Figure 30: Pareto Plot of Factor Effects to Structure Weight

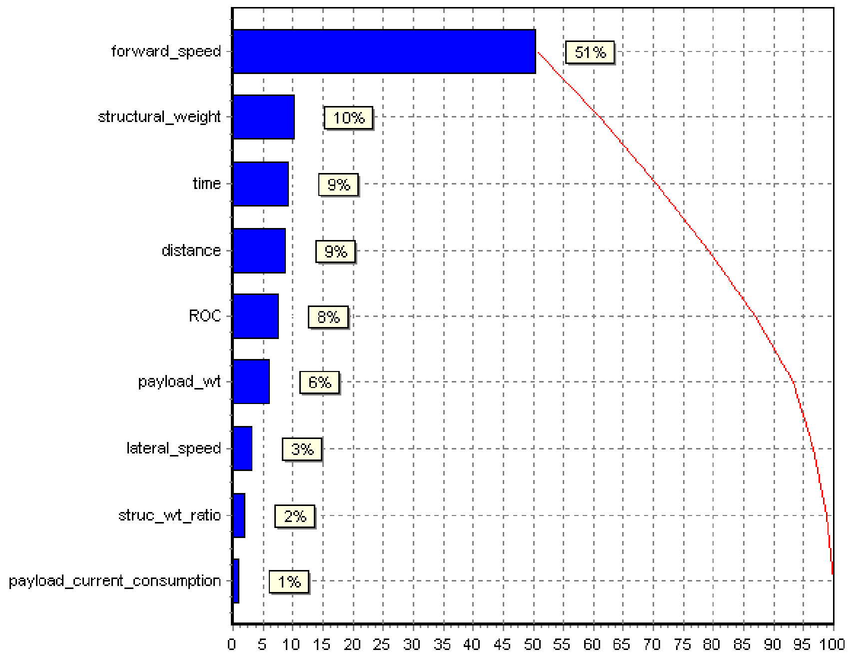

Figure 31: Pareto Plot of Factor Effects to Battery Weight

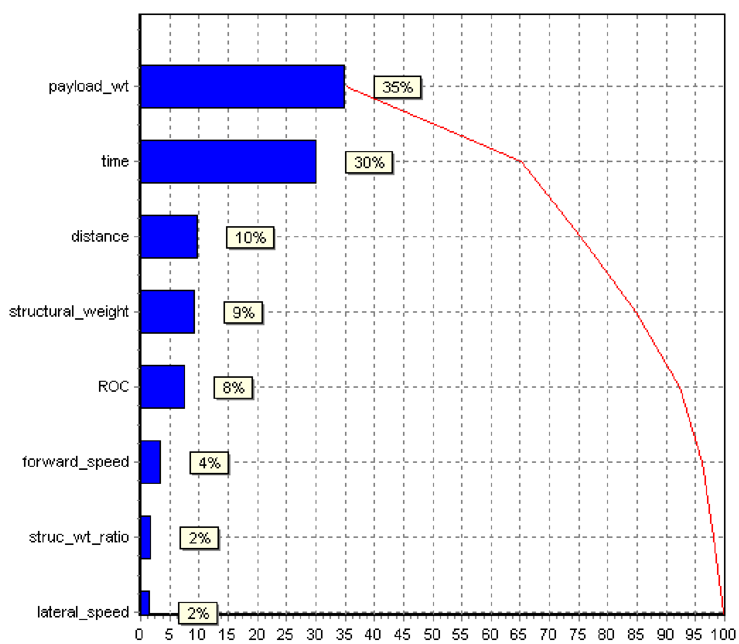

Figure 32: Pareto Plot of Factor Effects to HP Required

As it is apparent from Figure 29, forward speed and structural weight ratio are dominating factors for the total weight of the system. This is due to the motors size needed to generate the thrust required to get the vehicle to greater speeds. The structure fraction is obviously an important factor to total system weight. From Figure 30, the most influential factors to structural weight are the structure weight ratio and the forward speed. The structure weight ratio is directly related to the structure weight of the vehicle, and therefore its high relative importance is expected. The forward speed is also a major factor because, as emphasized earlier, forward speed determines size of motors and rotors required. Figure 31 shows that forward speed is the factor that affects battery weight the most, which is expected since increasing the speed required leads to required motors that run on higher energy required. The payload energy requirements stay fixed, whereas the motor energy requirements increase as the speed is increased. Finally, from Figure 32 payload weight and time of mission factors have the greatest effect on the power required. Increasing the payload weight leads to higher power required to flight at a given speed. And time of mission leads to increase of power required for flight and for dunning the payload sensors. Overall, the major contributing factors to the overall design of the vehicle are forward speed and structure weight, and should be considered more carefully in the design process.

1.7.6. S&S Environment

A Sizing and Synthesis (S&S) environment is being put together that integrates the S&S tools for small flapping wings and rotorcraft vehicles just described. This environment provides a stage to define vehicle requirements, physical configuration, and capabilities that are used to preliminarily determine the vehicle size and power source configuration. The end results are physical feasible vehicle solutions in the form of flapping wing and rotorcraft combinations that meet the requirements from simulations.

The layout of the S&S environment is shown in Figure 33. Once the high level simulations with USARSim are performed, the outputs of the simulation, such as range, speed, time to completion, and sensor capabilities are used as inputs to the S&S environment. Whether the simulation involved flapping wing vehicles only, or rotorcrafts only, or a combination of both, the respective outputs from the simulation are fed into the respective S&S model for flapping wing or rotorcraft vehicles.

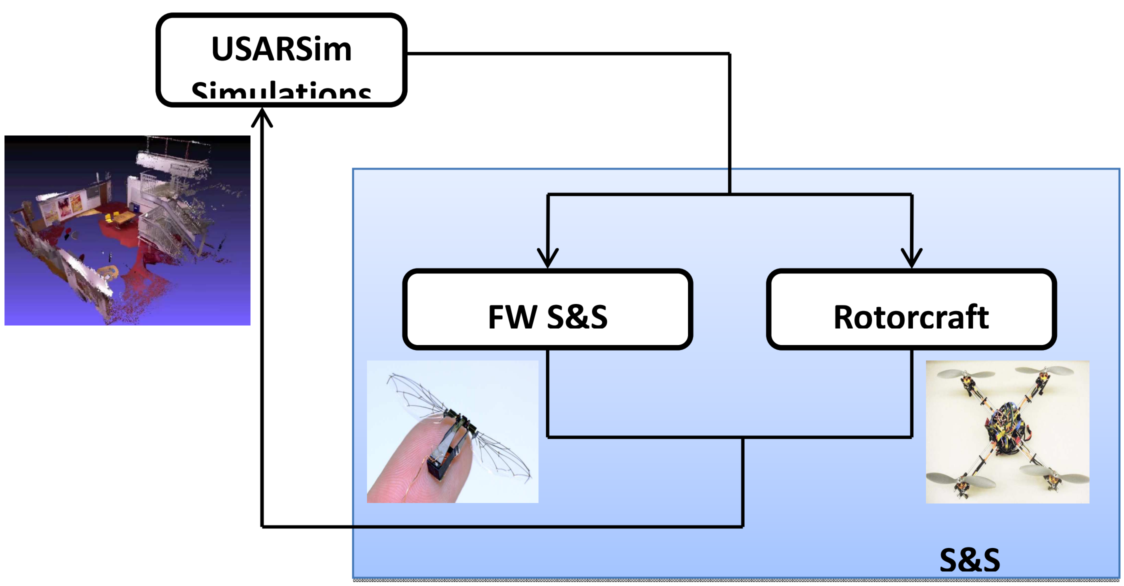

Figure 33: S&S Environment

The outputs of the simulations can be specified as ranges of possible allowable input values for the S&S environment to complete the mission, and in this case, a DOE is used to vary these metrics accordingly. If solutions are feasible, the iteration is complete, but if the solutions are not satisfactory or not feasible, the simulation is run again with different conditions, which leads to different required simulation metric values that can be tested for feasibility in the S&S environment. Figure 34 shows the process flow of the S&S environment using ModelCenter.

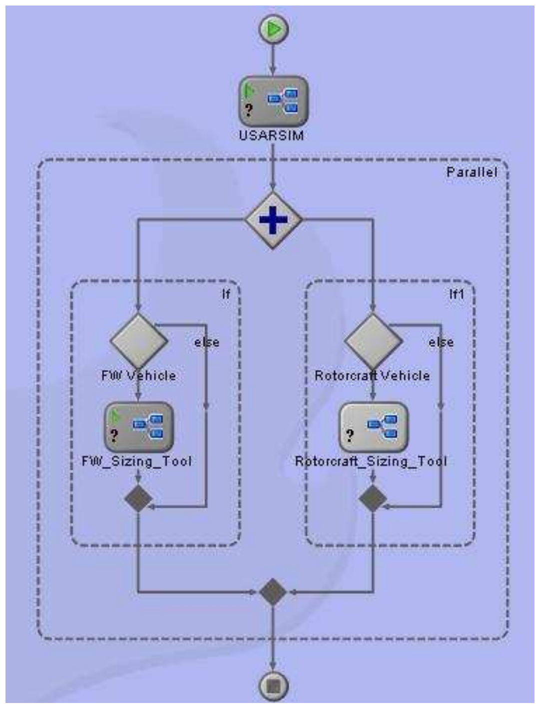

Figure 34: Process flow of S&S environment in ModelCenter

Results from this S&S environment provide a view of feasible solutions, and identifies capability and technology gaps that need to be addressed. This knowledge is in turn used for the development of these vehicles and as guidance to areas of improvement. In this way, the relationship between vehicle design characteristics and overall mission effectiveness can be mapped together for one or multiple micro-aerial vehicles of interest.

This S&S environment was used to map simulation results to physical characteristics and capabilities of the vehicles used during the simulation. The study only involves quad-rotors, since flapping wing vehicles have not been modeled in the simulation environments yet. This was done merely to show how the S&S environment interacts with the simulation environment. The USARSim simulation inputs and outputs were used to create a range of values that can be used as inputs to the S&S environment. These values are shown in Table 12.

Table 12: USARSim Simulation Input and Output Range of Values

Input Variable	Min Value	Max Value
Forward Speed (ft/s)	0.08	1.69
ROC (ft/min)	1.83	36.58
Distance Range (miles)	0.003	0.66
Lateral Speed (ft/s)	0.08	1.69
Time (min)	0	7
Payload current cons. (mA)	0.1	1

From these input variable ranges, a Latin Hypercube DOE was used to explore the interior of the design space since more importance was placed on the continuous interior design space rather than on the extreme edges of the space. The pareto plots in Figure 35 and Figure 36 show the effects of the different input variables to the total gross weight of the system and the power required, respectively.

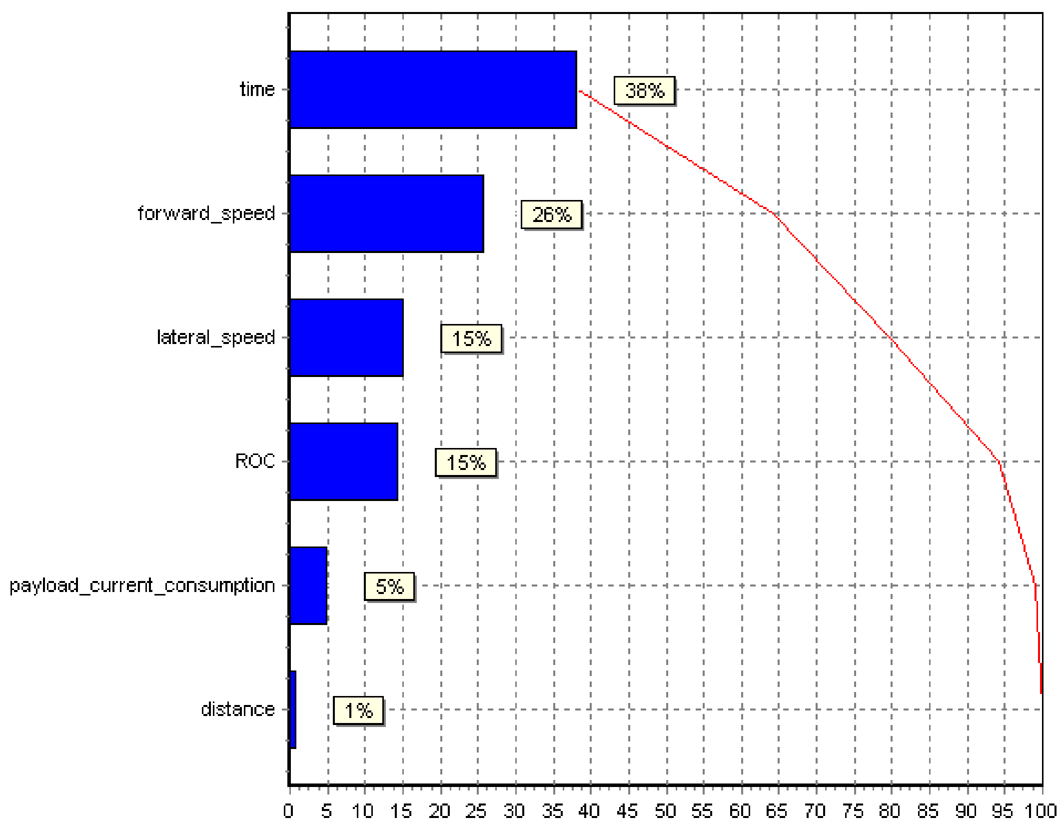

Figure 35: Pareto Plot of Total Gross Weight

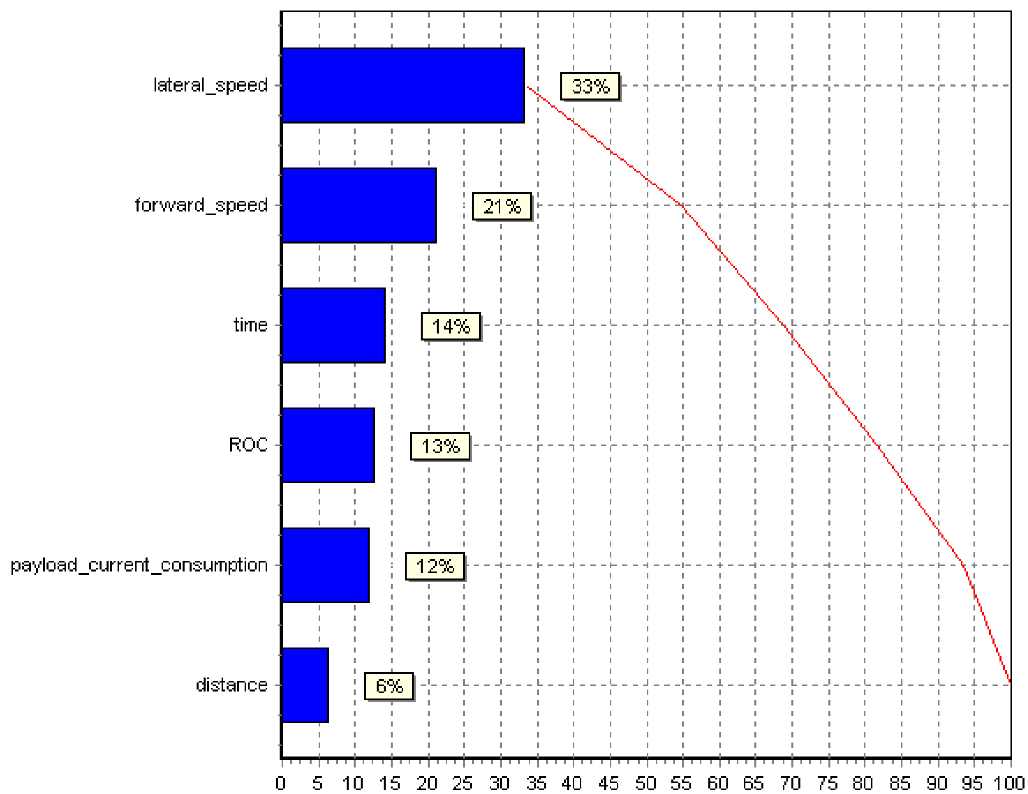

Figure 36: Pareto Plot Power Required

From Figure 35, the major contributor to total system gross weight is the time of the mission. This is intuitively since the longer the mission, the more power required to flight and the greater the battery size required. Forward speed is also a major contributor to gross weight since as the speed is increased; the motors and rotors get bigger and heavier and require more power which leads to larger battery size. From Figure 36, the major contributor to the power required is the lateral speed since it requires more power to move laterally and forward than just forward alone. A prediction profile is also used to move design points around and see the effects of individual input variables on the responses of interest.

As noted earlier, the factors that affected the gross weight the most were found to be time and forward speed. Figure 37 and Figure 38 show the gross weight responses as a function of time and forward speed, respectively, excluding and including the bad cases.

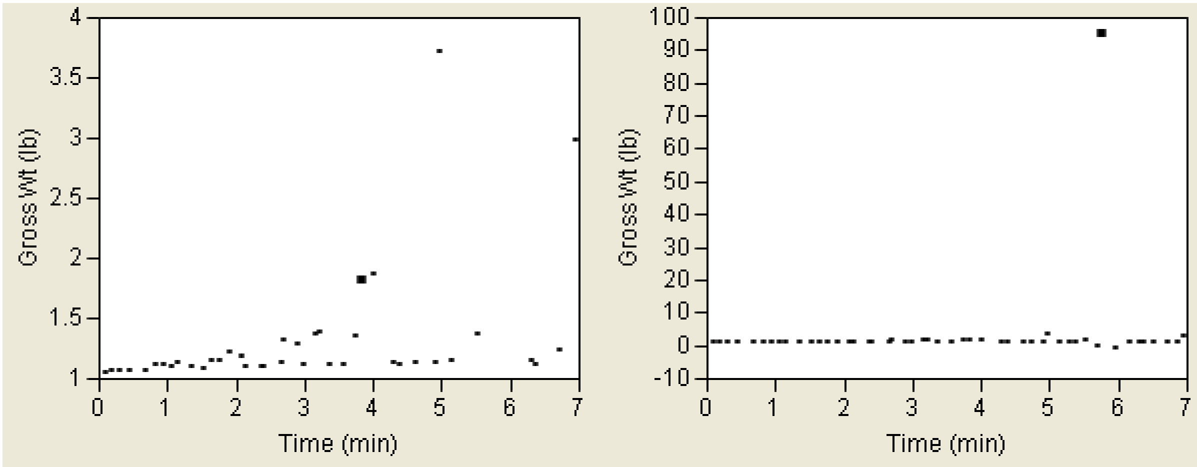

Figure 37: Gross weight Vs time for feasible solutions (left) and including infeasible solutions (right)

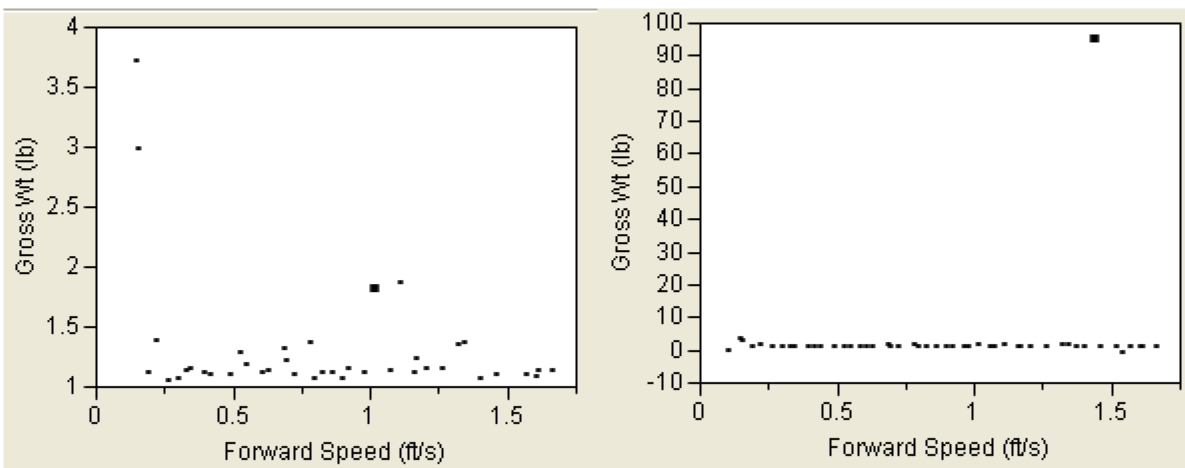

Figure 38: Gross weight Vs speed for feasible solutions (left) and including infeasible solutions (right)

Not all of the simulation solutions were feasible, as can be easily noticed in Figure 37 and Figure 38 by the outlier points. 20 % of all the cases ran showed non-feasible solutions. These non-feasible solutions showed non-physically possible configurations such as negative gross weight and negative battery sizes. These failed cases will need to be investigated further and validated with experts in the field to determine the gaps that need to be filled in with technology and vehicle capabilities. The solutions that were feasible were used to explore the design space within the ranges used in the simulation.

The S&S environment has been used in parallel with the USARSim simulations so far, taking the ranges of values from the simulations, and exploring the S&S design space within those ranges to determine the effects of different factors on the size of the vehicle. Rather than running in parallel, the goal in the near future is to have the S&S environment run in series with the USARSim simulations. As soon as a simulation case is done in USARSim, these outputs form simulation, and the values which make the simulation unique, are fed to the S&S environment to determine if there is a physically feasible vehicle solution possible, and if there is it will also give specifications on the configuration and the size of the vehicle. If there are no physically feasible vehicle solutions for that case, then this information is fed back to the USARSim environment to consider running the same case using other input parameters. This is done until the USARSim and S&S environment converge to a physically feasible solution. This is already being modeled in ModelCenter, but the interaction between the USARSim simulation codes and the S&S environment still needs further effort. A schematic of the process flow is shown in Figure 39.

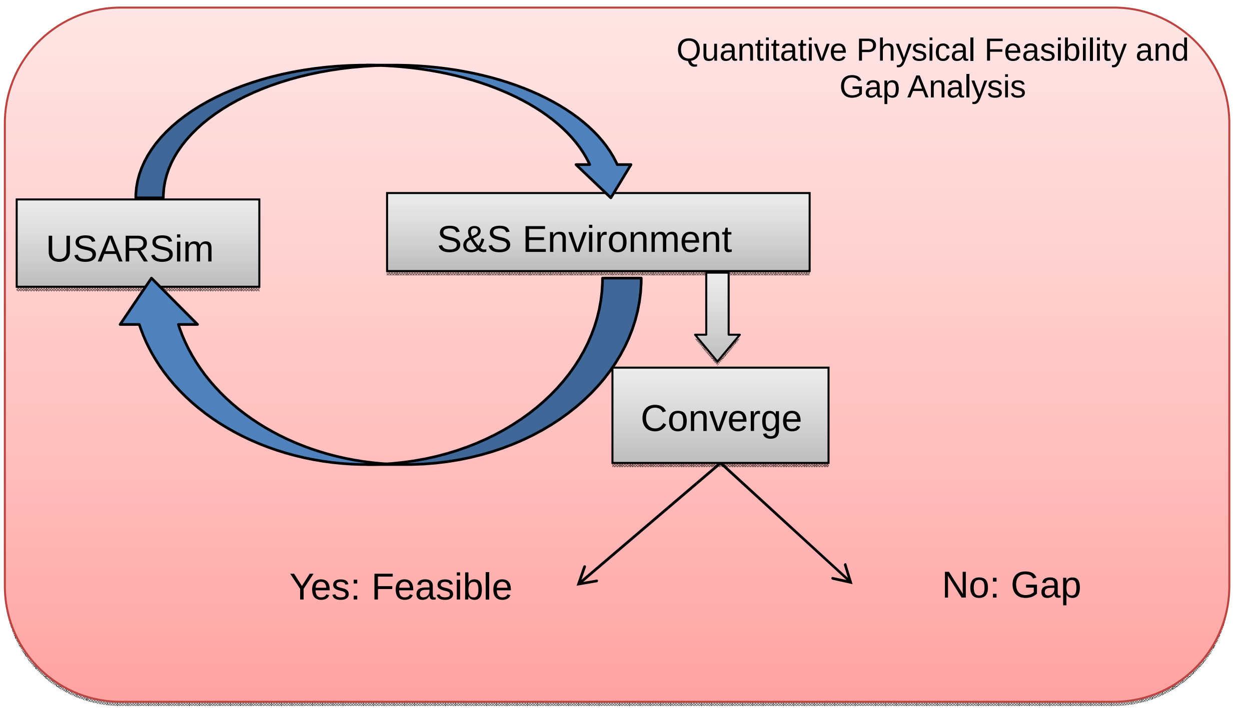

Figure 39: Process flow of Quantitative Physical Feasibility and Gap Analysis

In the near future, this S&S environment will be upgraded further to account for physical characteristics of these micro-aerial vehicles that are crucial for their performance and capability. One such important physical characteristic is the flapping wing topology and mechanism configuration in flapping wing vehicles. A structural analysis will be conducted using Multi Body Dynamics (MBDyn) to model and simulate complex wing shapes and actuator dynamics to determine allowable flapping frequencies and amplitudes for given wing kinematics.

Another area for improvement in this S&S environment is to expand the database of available motor, transmission, and speed controller configurations available for different size of aerial vehicles. The payload database is also being constantly upgraded based on available data from the consortium, but there are still certain attributes that need to be specified and need to be taken into account with certain accuracy to be able to model these systems appropriately. These include physical dimensions and weight fractions of new technologies and sensors that are being used in these aerial vehicles.

2. Planned activities and milestones for the next quarter

With all the major components nearing completion and being tested using sample cases, the focus of next year will be to primarily run actual MAST mission scenarios and quantity operational disconnect and technology gap. In a nutshell, the next quarter will have focus on completion and launch of W-IRMA, further simulation runs and development, final software patches on the physical quad-rotor, and finally compilation of all the data gleaned from the aforementioned steps. A timeline for this planned next quarter work is shown in figure below.

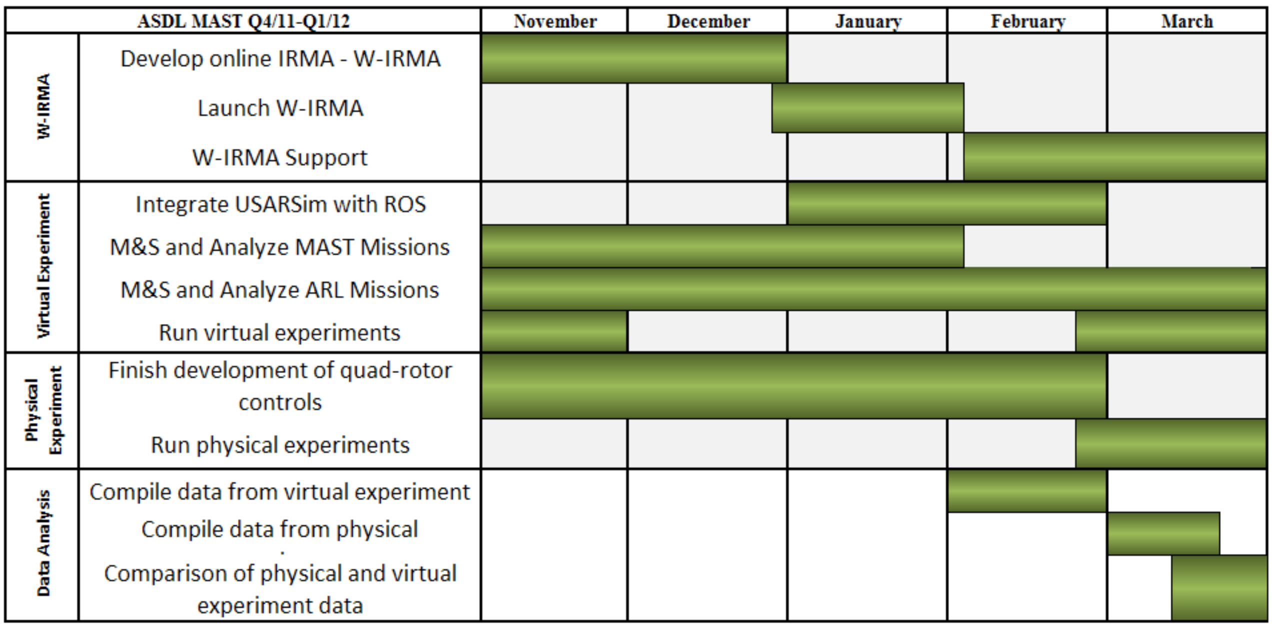

Figure 40: Gantt Chart of Planned Activity

3. Publications or patents.

4. Collaborative activities.

5. Changes in key personnel.

Investigators: Dr. Dimitri Mavris, Carl Johnson

Lead Student Researcher: Zohaib Mian

Student Researchers: Patrick Dees, Tim Dyer, Leslie Hall, Steven T. Jackson, Pierre Valdez

Grand Challenge Team (September 2011 – May 2012): Aaron Mosher, Michael Looby

6. Unexpected trouble.